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Problems Facing Coal Mining and Gas Production in the Hartshorne Coalbeds of the Western Arkoma Basin, OK

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
James G. Watt, Secretary

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m	meter
cm^3/g	cubic centimeter per gram	m^3	cubic meter
ft	foot	m^3/d	cubic meter per day
ft^3	cubic foot	md	millidarcy
ft^3/d	cubic foot per day	mi	mile
ft^3/T	cubic foot per ton (short)	Pa	Pascal
gal	gallon	pct	percent
in	inch	t	metric ton
km	kilometer	T	ton (short)
L	liter	yr	year

PROBLEMS FACING COAL MINING AND GAS PRODUCTION IN THE HARTSHORNE COALBEDS OF THE WESTERN ARKOMA BASIN, OK

By A. T. Iannacchione,[1] C. A. Kertis,[1] D. W. Houseknecht,[2] and J. H. Perry[3]

ABSTRACT

Major problems facing the development of coal and gas resources of the Hartshorne Coalbeds include the complex distribution of minable and unminable coal, high methane content and bed pressure, faulting, variations in degree of dip, presence of natural gas fields in associated sandstones, and legal problems, caused by local geologic characteristics, in identifying gas origin. This Bureau of Mines study provides pertinent geologic information for long-range planning of subsurface coal and gas production from the Hartshorne Coalbeds.

Pittsburg, Coal, Hughes, and Atoka Counties, OK, have approximately 1 billion metric tons (1.1 billion short tons) of Hartshorne coal in place. The methane resource of Hartshorne Coalbeds is estimated at 9.2 billion m^3 (325 billion ft^3) and varies with overburden and rank. These estimates were compiled from gas well density logs, coal-core data, outcrop measurements, abandoned mine maps, and the literature.

The Hartshorne Coalbeds represent a valuable coal and gas resource which at present is contributing nothing to coal and gas production. This report discusses potential problems and serves as a reference for future exploration and development work. Recognition of these potential geologically related problems prior to development of this basin will reduce hazards and allow for an economic recovery of these resources.

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INTRODUCTION

The Hartshorne Coalbeds of the western Arkoma Basin (fig. 1) contain some of the better quality metallurgical and steam coals found west of the Mississippi River. These coalbeds were mined extensively along outcrops from the 1870's to the early 1950's. In 1915, 100 pct of the mining was done by underground methods. This percentage has decreased steadily through the years to zero by 1970. Recent attempts to mine the Hartshorne Coalbeds, such as the Howe, Evans Experimental, and Choctaw Mines, have all failed after initial development. Excessive methane emissions, steeply dipping beds, variable overburdens [0 to 1,220 m (0 to 4,000 ft)], discontinuities of coal from faults and "wants" (wants indicate a lack of minable thickness), and poor roof-rock stability have all combined to threaten the safety of miners and to hinder coal production.

Methane gas production has been demonstrated at two locations in the basin and shows great potential even though the Hartshorne Coalbeds are known to have generally low permeability. Kissell (22)[4] indicated permeability ranges of 0.08 to 2.0 md from nine horizontal holes 18 to 34 m (60 to 110 ft) long at the Howe No. 1 Mine in Le Flore County, OK. This same mine was the site of a five-hole vertical methane drainage project. Production from the pattern totaled 141,500 m^3 (5 million ft^3) of methane gas and 382,000 L (101,000 gal) of water over a 3-yr period (7). The depth of these holes ranged from 152 m (500 ft) to 183 m (600 ft). One hole in this pattern was stimulated and showed an eightfold increase in methane production.

Kerr-McGee drained methane from the Hartshorne Coalbeds at its Choctaw Mine from 1976 to 1979. A number of horizontal boreholes 60 to 750 m (200 to 2,500 ft) long were drilled into the coalbed. Gas production from these holes reached a high of 28,000 m^3/d (1 million ft^3/d) in 1977 and decreased to approximately 11,000 m^3/d (400,000 ft^3/d) in

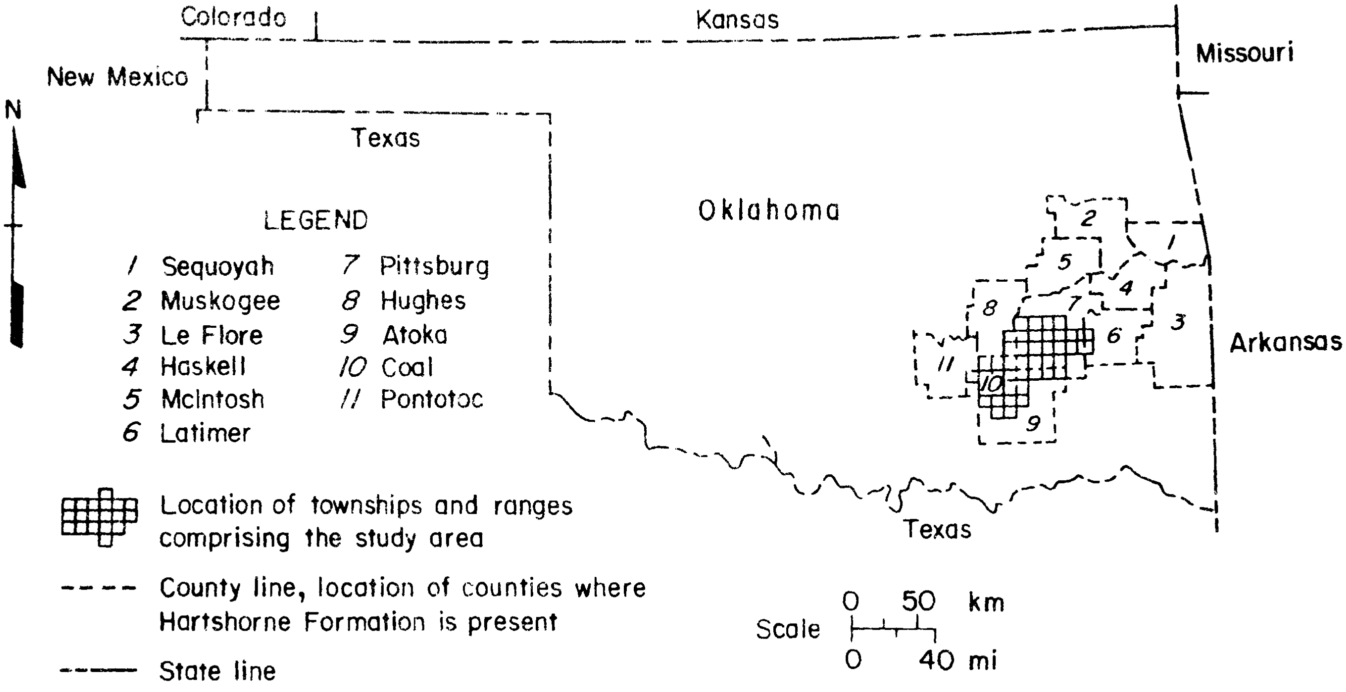

FIGURE 1. - Location of study area; portions of Pittsburg, Coal, Hughes, and Atoka Counties, OK.

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[4] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

mid-1978 (30). Information from these two demonstration projects, together with methane content and coal thickness data from this report, shows an excellent potential for gas production from Hartshorne Coalbeds.

It is expected that the collection, examination, and distribution of data concerned with mining and methane drainage of the Hartshorne Coalbeds will increase interest and aid in planning safer, more efficient operations. Geologic maps, coal-core desorption data, physical and chemical gas composition data, and discussions of methane drainage technologies are presented herein to provide a basis for understanding fundamental factors controlling mining and gas production from the Hartshorne Coalbeds of the western Arkoma Basin.

ACKNOWLEDGMENTS

Special cooperation in data collection was provided by the coal and gas operators of the Arkoma Basin. The authors also wish to thank V. G. Iannacchione of Research Triangle Institute, Raleign, NC, for his input in the statistical interpretation of the data.

THICKNESS AND AREAL EXTENT OF THE HARTSHORNE COALBEDS

An accurate estimate of total coal in place in the western Arkoma Basin has been difficult to make because of the lack of borehole data and poor outcrop exposure. To compensate for this lack of information, readily available density logs from numerous gas wells have been conservatively evaluated to estimate coal thickness. The resources of Hartshorne Coalbeds [greater than 36 cm (14 in) thick and less than 914 m (3,000 ft) deep] have been calculated to be approximately 1 billion t (1.1 billion T). Approximately 900 million t (1 billion T) of the resources is contained in Hartshorne Coalbeds greater than 71 cm (28 in) thick. This estimate does not include approximately 27 million t (30 million T) of coal already mined. Using coal-core, outcrop, and mine data, Friedman (10) previously set an estimate of coal resources for Pittsburgh, Coal, and Atoka Counties at 566 million t (624 million T).

USE OF GAS WELL DATA TO IDENTIFY OCCURRENCE OF HARTSHORNE COALBEDS

The Bureau has attempted to estimate tonnage of minable coal in place so that methane resources can be calculated for deep mining and degasification projects. Until recently, exploration coal-core drilling has occurred almost exclusively within 2 km (1.25 mi) of the outcrop of the Hartshorne Formation. For the most part, coalbed resources greater than 2 km (1.2 mi) from outcrop and greater than 300 m (1,000 ft) deep have been considered unknown. However, in the next few decades coal mining will probably occur at depths approaching 900 m (3,000 ft).

Isopach maps of the Hartshorne Coalbeds [figs. 2 and 3 (envelope)] have been prepared from approximately 138 density logs from the more than 400 electric logs examined [fig. 4 (envelope)], maps from 34 abandoned coal mines, 5 coal-core logs, and outcrop data from published reports (4, 8-10, 12, 25, 28). It is not the purpose of this report to develop coal resource data, however, the U.S. Bureau of Mines and U.S. Geological Survey method (32) is used for calculating coal in place. Coal estimates are based on centers of circles with radii of 3 km (2 mi) from a borehole. Estimates of economic thicknesses are based on thicknesses greater than 71 cm (28 in). Table 1 contains a list of the economic resource estimates for the Hartshorne Coalbeds. The overall great depth of the coal is evident from these data because approximately 500 million t (550 million T) of coal, or over 50 pct of the remaining resources, occur at depths of 600 to 900 m (2,000 to 3,000 ft).

TABLE 1. - Economic resource estimates for the Hartshorne Coalbeds [>71 cm (>28 in)], million metric tons

Overburden, m	Undivided	Upper	Lower	Total	Portion of total resource, pct
0 to 305.....	0	60	105	165	18
305 to 610...	90	75	70	235	26
610 to 914...	175	180	150	505	56
Total.....	265	315	325	905	100

INFLUENCE OF DEPOSITIONAL ENVIRONMENTS ON THICKNESS OF THE HARTSHORNE COALBEDS

The depositional environments of the Hartshorne Coalbeds have influenced the thickness and areal extent of minable coal resources. Within the study area, the Hartshorne Formation has been subdivided (informally) by McDaniel (24) into a lower sandstone and coalbed member, and upper sandstone and coalbed member (fig. 5). The Lower Hartshorne member represents widespread prodelta and delta-front shale and sandstone facies capped by thick [30 m (91 ft)], linear [2-4 km (1-2 mi) wide, 48-64 km (30-40 mi) long] distributary channel sandstone facies which interfinger laterally with thinner interdistributary bay facies (fig. 6). Paleocurrent analyses indicate that the direction of sediment transport in the delta complex was from east to southwest (15).

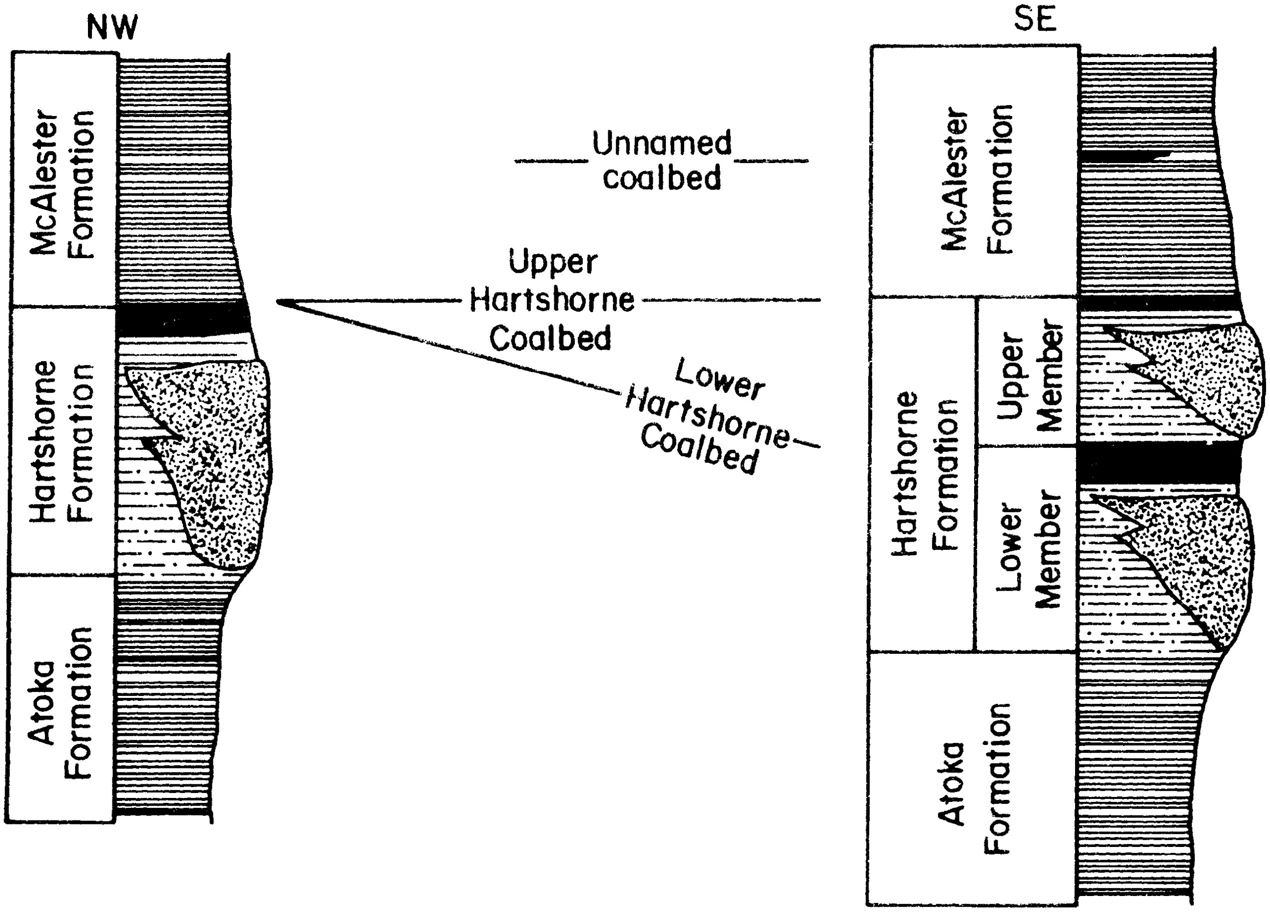

FIGURE 5. - Generalized stratigraphic cross section of the Hartshorne Formation, western Arkoma Basin.

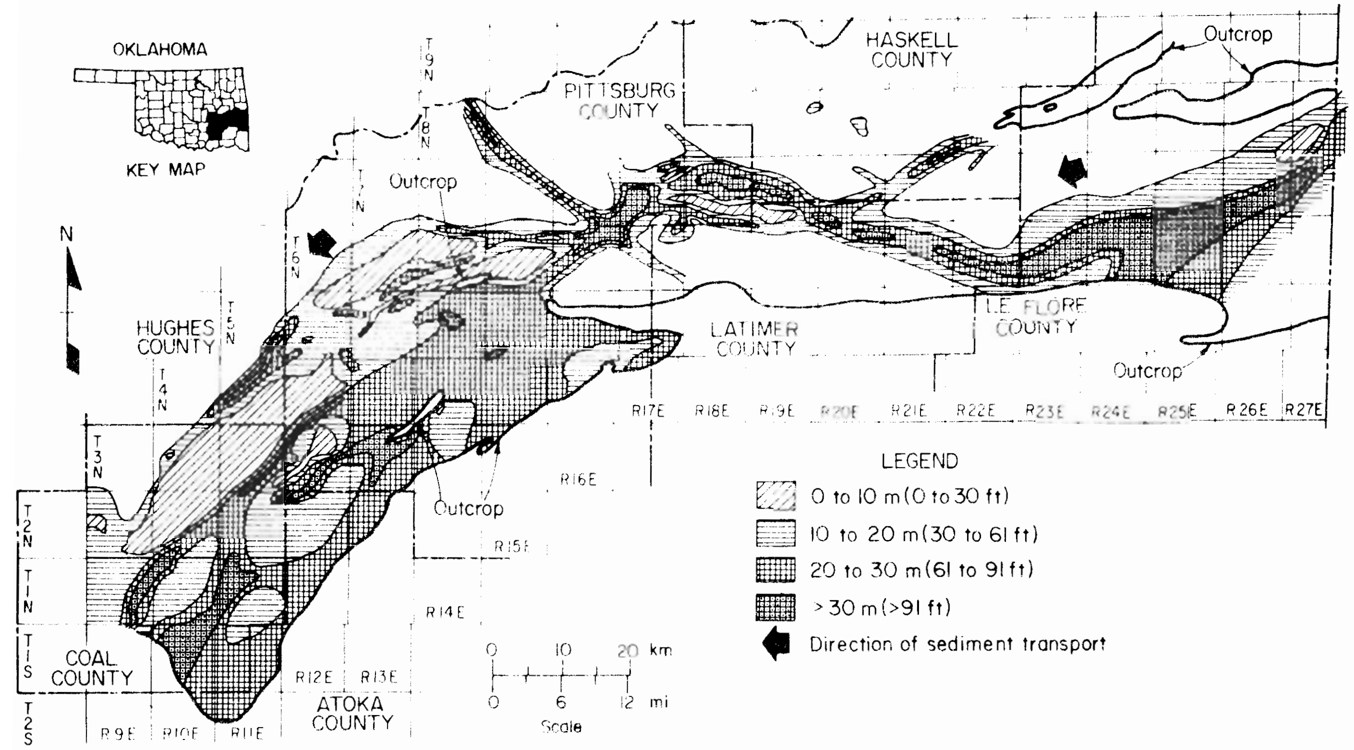

FIGURE 6. Lower Hartshorne Sandstone regional isolith map.

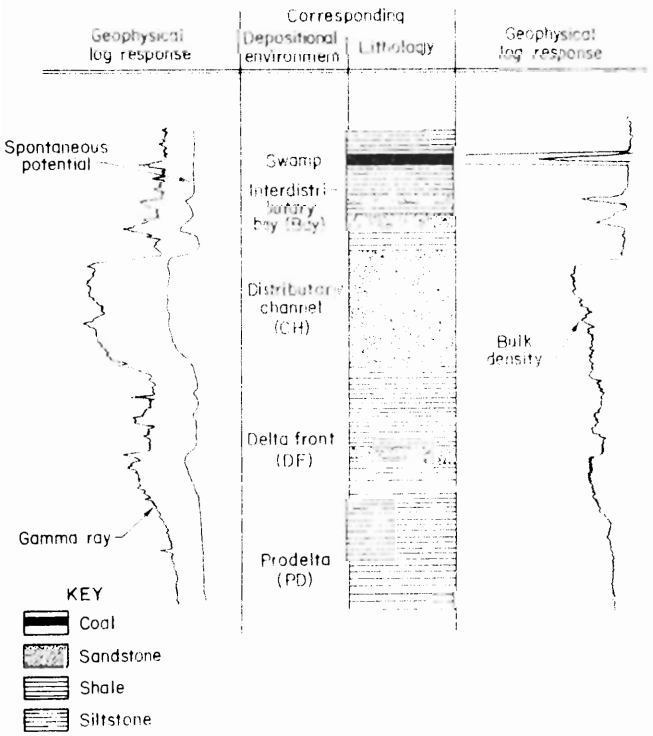

FIGURE 7. - Example of depositional environment and lithology identification from geophysical log responses.

Information from geophysical gas well logs was used for stratigraphic correlations and lithologic identification (fig. 7). Stratigraphic cross sections (figs. 8-10) were constructed from gamma ray, spontaneous potential, and resistivity logs. The locations of these cross sections are shown in figure 11. Cross sections are constructed perpendicular to the trend of the linear "shoestring" distributary channel sandstones.

The entire Hartshorne Formation thickens from northwest to southeast across the study area as indicated by the cross sections (figs. 8-10). The Hartshorne Coalbed splits along this trend into an upper and lower coalbed. Four major channel deposits were recognized in the Lower Hartshorne member and one major channel deposit in the Upper Hartshorne member. The percentage of sandstone in the Lower Hartshorne member increases to the southeast. In contrast, the Upper Hartshorne member contains its greatest percentage of sandstone directly to the southeast of the coal-split line in the center of the basin (fig. 12).

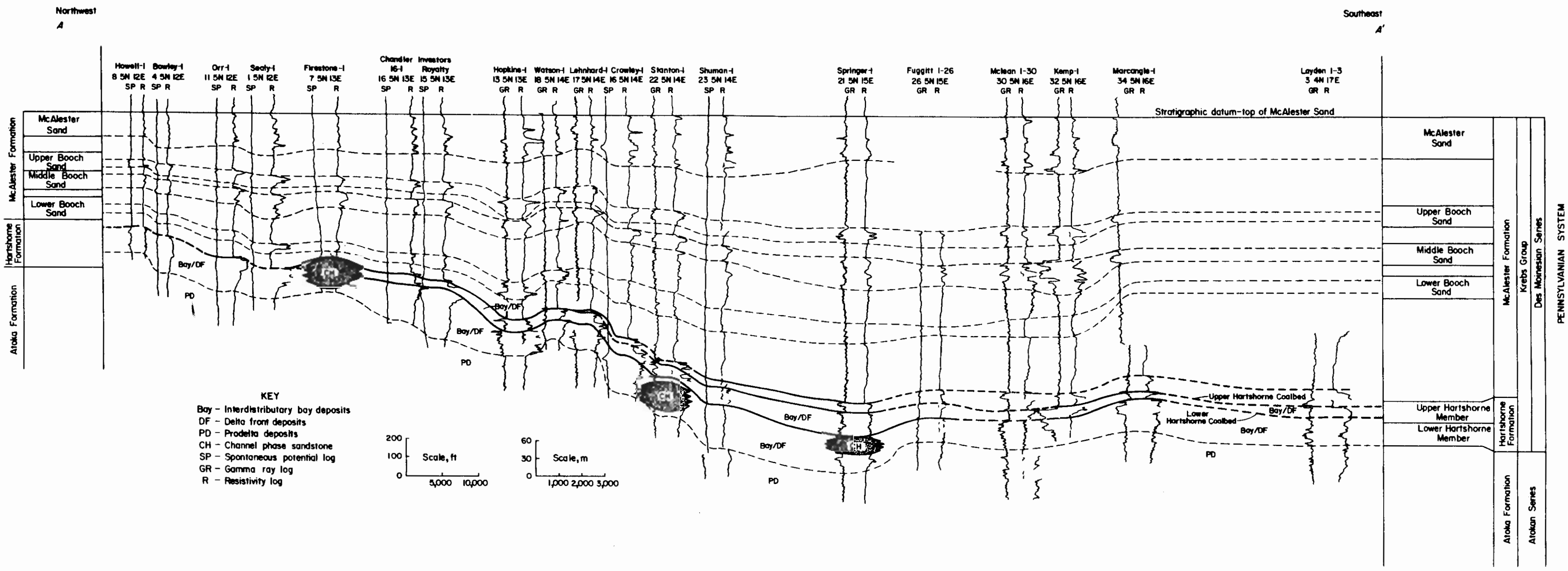

FIGURE 8. - Northwest to southeast stratigraphic cross section A-A' through the northern portion of the study area.

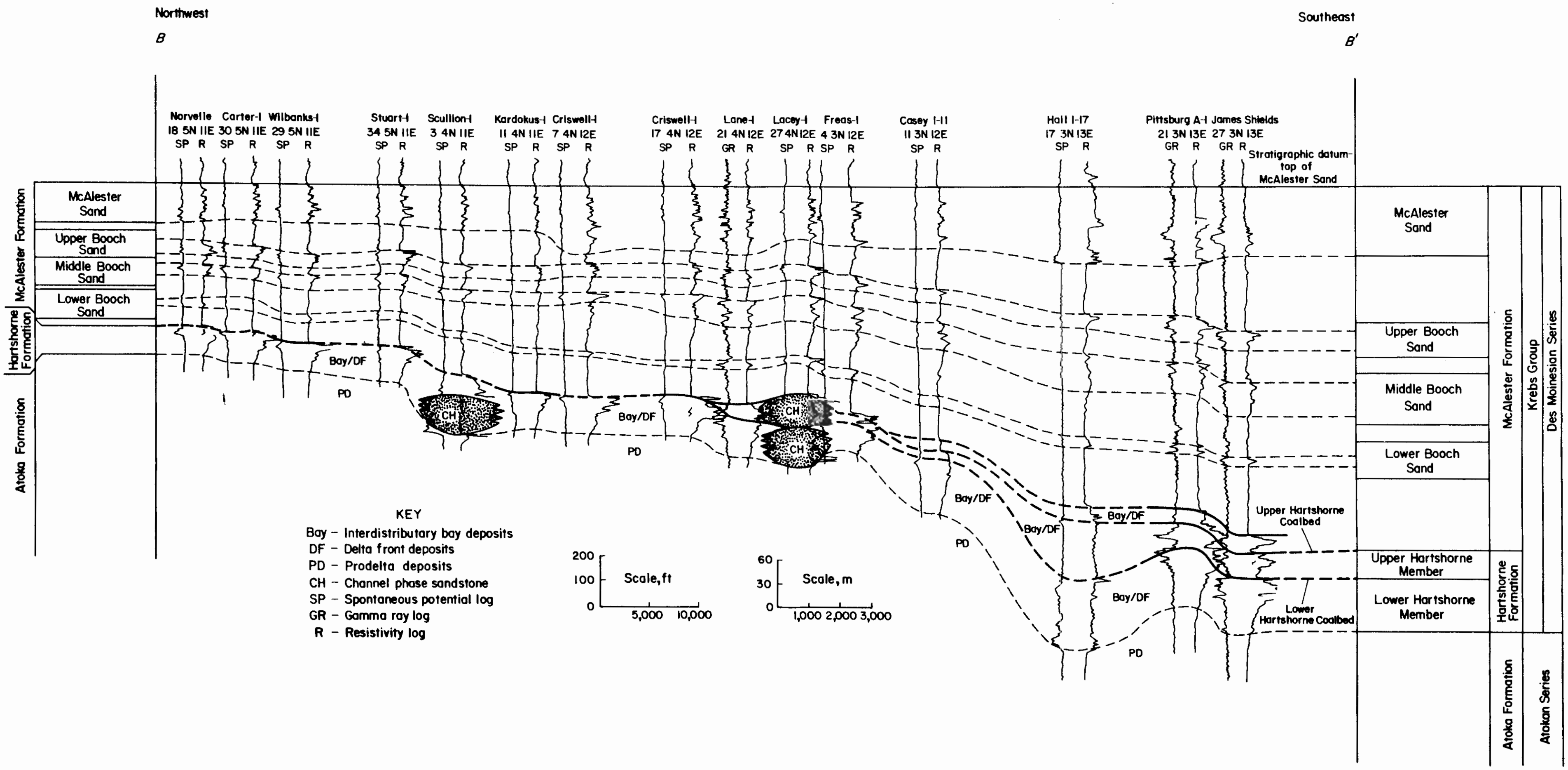

FIGURE 9. - Northwest to southeast stratigraphic cross section B-B′ through the central portion of the study area.

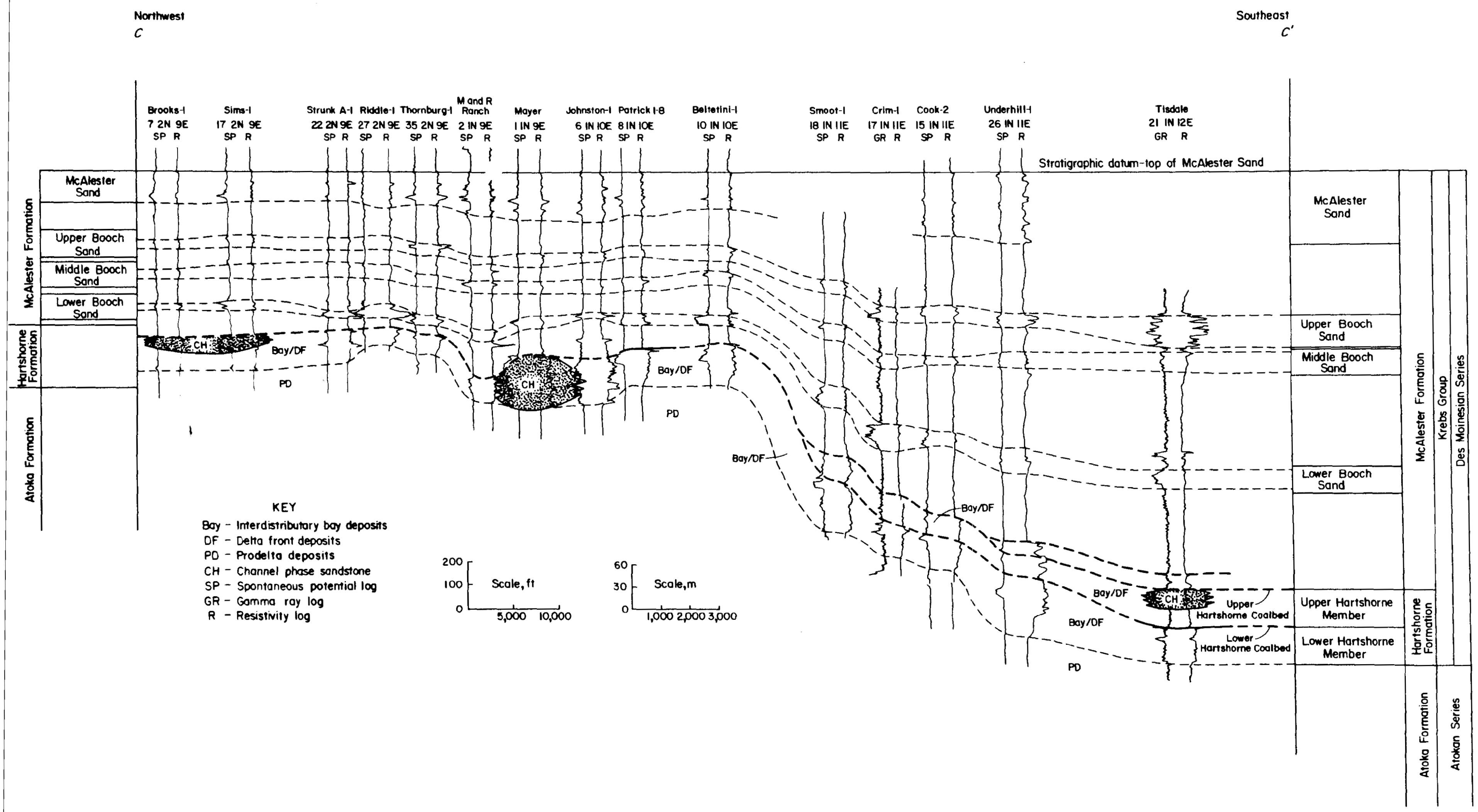

FIGURE 10. - Northwest to southeast stratigraphic cross section C-C' through the southern portion of the study area.

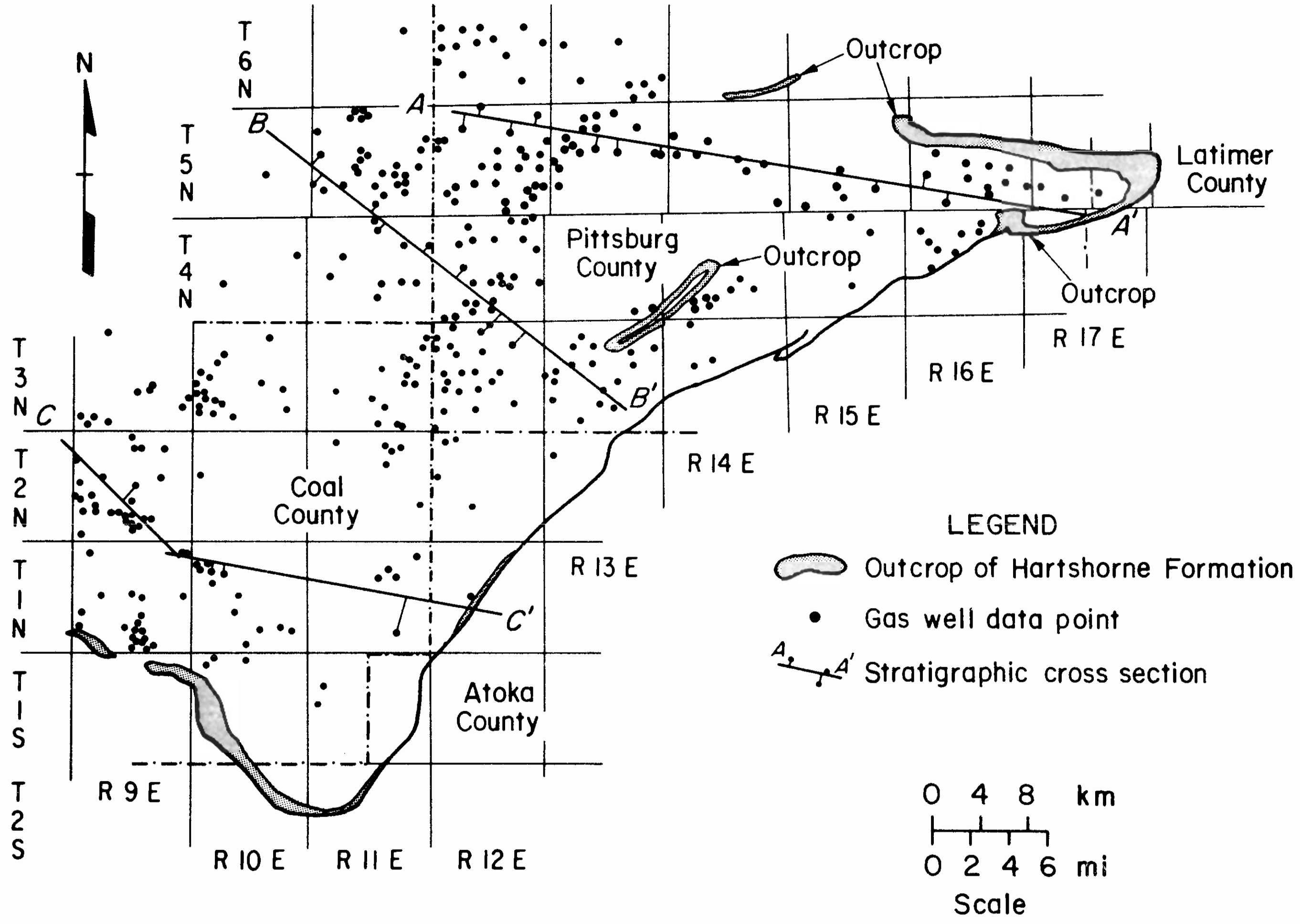

FIGURE 11. - Location of stratigraphic cross sections.

These distributary channel deposits directly affect the thickness and areal extent of the Hartshorne Coalbeds. Areas of thick Lower Hartshorne Sandstone [fig. 13 (envelope)] coincide with areas of thin or absent Hartshorne (undivided) and Lower Hartshorne coal (fig. 3). Similarly, areas of thick Upper Hartshorne Sandstone [fig. 14 (envelope)] coincide with areas of thin or absent Upper Hartshorne coal (fig. 4). Generally, wherever the sandstone is more than 20 m (61 ft) thick, the overlying coalbed is too thin to mine economically. This association of thick sandstone with thin overlying coal suggests that sand bodies acted as topographic highs upon which thick peat could not accumulate in Hartshorne coal swamps (14).

Additionally, areas of thick Upper Hartshorne Sandstone (fig. 14) commonly coincide with areas of thin or absent Lower Hartshorne coal (fig. 3). Houseknecht and Iannacchione (14) have suggested that the lower coal, or more likely its peat precursor, was eroded by distributary channel processes prior to deposition of the thick upper sand. Because of these relationships, areas with few density logs associated with thick sandstone [20 m (61 ft)] were considered to have uneconomic thicknesses of coal.

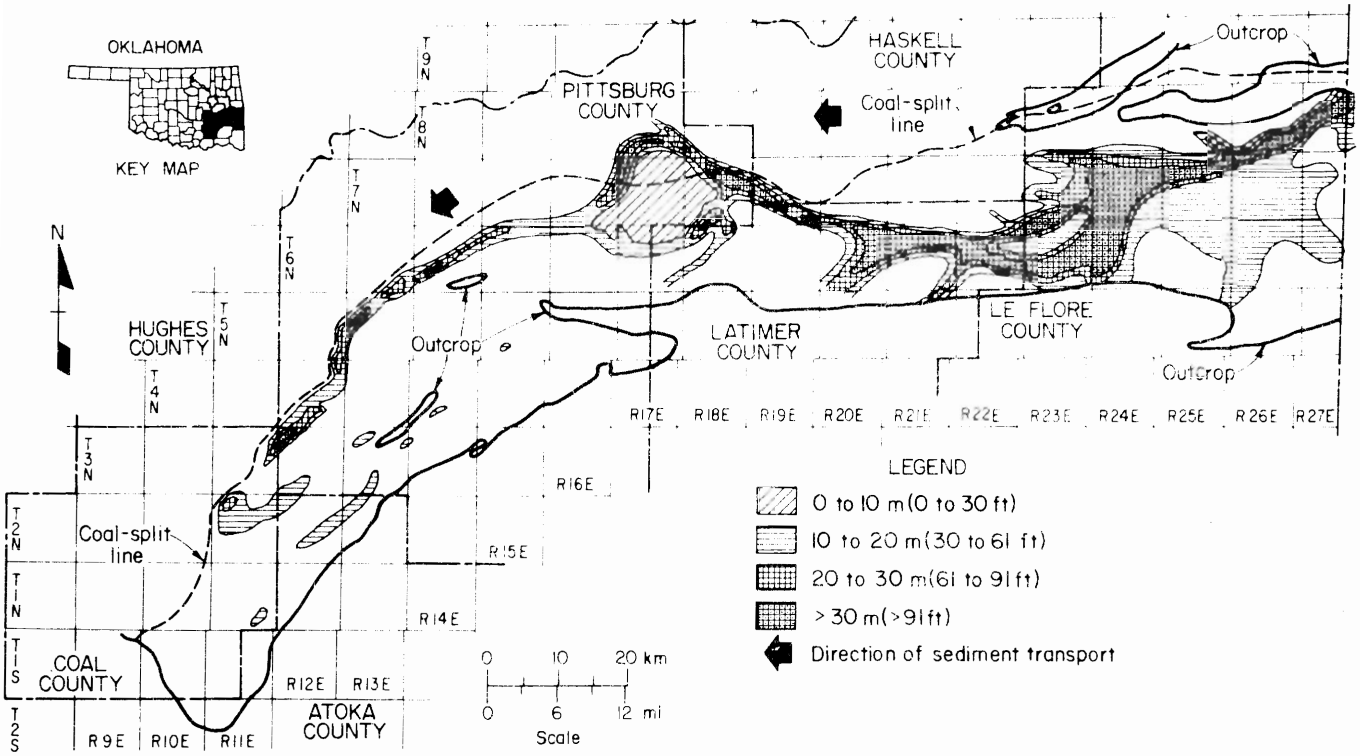

FIGURE 12. - Upper Hartshorne Sandstone regional isolith map.

METHANE CONTENT OF THE HARTSHORNE COALBEDS

The Hartshorne Coalbeds of Oklahoma are among the most gassy coalbeds in the United States. Investigation of methane content aids in establishing the safety hazards for future underground mines and also delineates the potential for a profitable energy resource. Thick overburden [0 to 1,500 m (0 to 460 ft)] and relatively high rank (high-volatile C to high-volatile A bituminous) are the two most significant factors affecting high methane content. Methane resources were estimated by calculating the amount of coal in place at various overburden intervals and multiplying this figure by the estimated methane content.

VARIATION OF METHANE CONTENT WITH OVERBURDEN AND RANK

Hartshorne coal-core desorption samples (table 2) were collected throughout the Oklahoma portion of the Arkoma Basin (fig. 15). Depths of samples ranged from 53 to 439 m (175 to 1,439 ft). Coal rank varied from high-volatile C to low-volatile bituminous from west to east across the Oklahoma portion of the basin (fig. 16). The methane content of each sample was determined using the Bureau of Mines direct method test as described by Diamond and Levine (5). Gas content of the samples ranges from 2.5 to 17.5 cm^3/g (80 to 560 ft^3/T). The relationship among overburden, rank, and methane content is shown graphically in figure 17.

Large variations in overburden [fig. 18 (envelope)] and rank (fig. 16) indicate a need to estimate methane content for separate overburden intervals of different rank coals. Methane content has been observed to increase exponentially with increasing overburden (21). Rank also influences methane content. The amount of methane evolved during coalification and the ability of coal to store methane increases as rank increases

TABLE 2. - Hartshorne coal-core desorption analysis

Sample	Coalbed	County	Township and range	Depth, m	Methane content, cm^3/g	Rank[1]
1.....	Lower....	Le Flore.	24 T8N R25E	97	8.7	LVB
2.....	Undivided	...do....	29 T9N R26E	149	11.2	LVB
3.....	...do....	...do....	29 T9N R26E	157	11.8	LVB
4.....	...do....	...do....	29 T9N R26E	171	11.5	LVB
5.....	...do....	...do....	28 T9N R26E	174	11.8	LVB
6.....	...do....	...do....	21 T9N R26E	149	10.9	LVB
7.....	...do....	...do....	29 T9N R26E	77	5.7	LVB
8.....	...do....	...do....	28 T9N R26E	53	2.5	LVB
9.....	...do....	...do....	22 T9N R26E	169	10.9	LVB
10....	...do....	...do....	23 T9N R26E	109	10.8	LVB
11....	...do....	Haskell..	12 T8N R21E	395	17.5	MVB
12....	...do....	Le Flore.	22 T9N R25E	439	16.7	LVB
13....	Lower....	...do....	1 T5N R25E	169	13.1	LVB
14....	...do....	...do....	29 T9N R26E	272	16.8	LVB
15....	Upper....	...do....	29 T8N R26E	251	15.5	LVB
16....	Lower....	...do....	8 T8N R27E	60	9.7	LVB
17....	...do....	...do....	26 T8N R23E	236	11.7	LVB
18....	Upper....	Pittsburg	21 T5N R16E	265	9.0	HVAB
19....	Lower....	...do....	21 T5N R16E	278	8.3	HVAB

[1] LVB, low-volatile bituminous coal; MVB, medium-volatile bituminous coal; HVAB, high-volatile A bituminous coal.

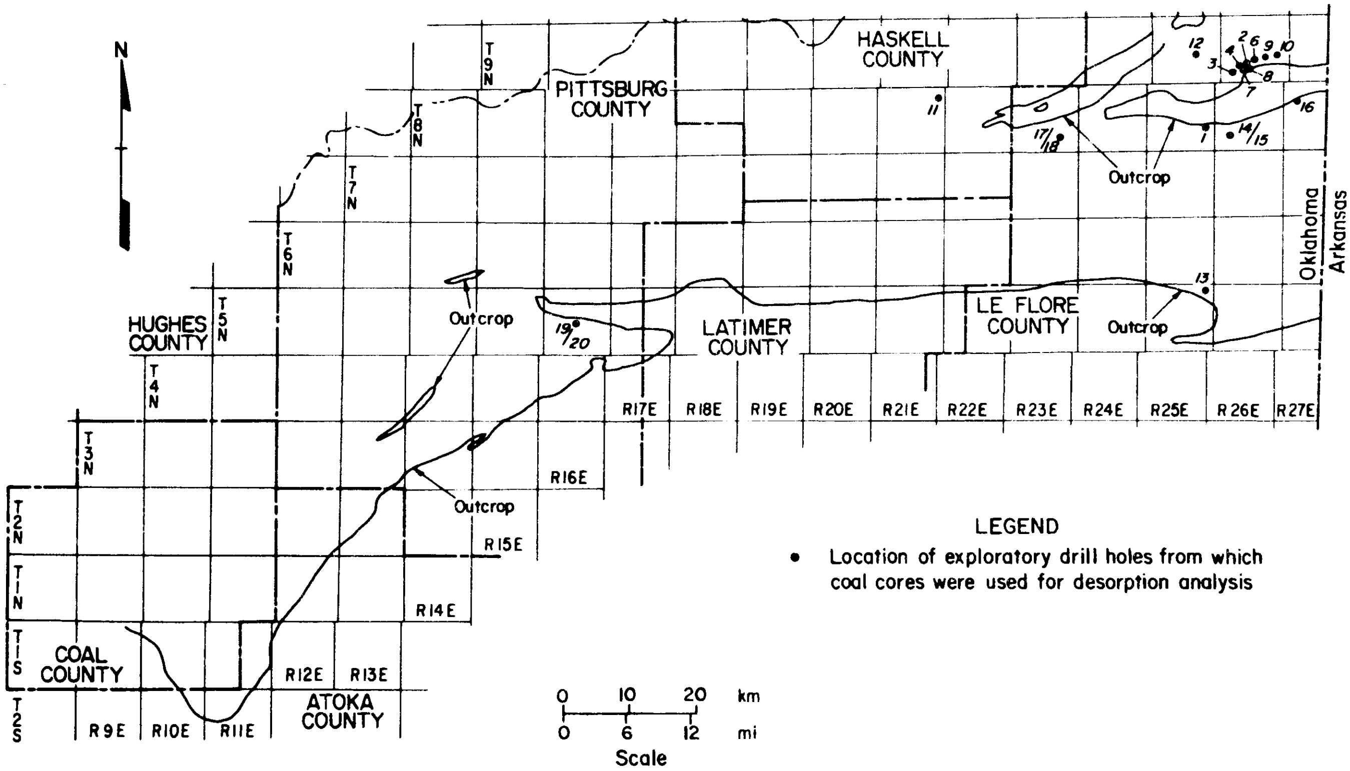

FIGURE 15. - Location of Hartshorne coal-core desorption samples.

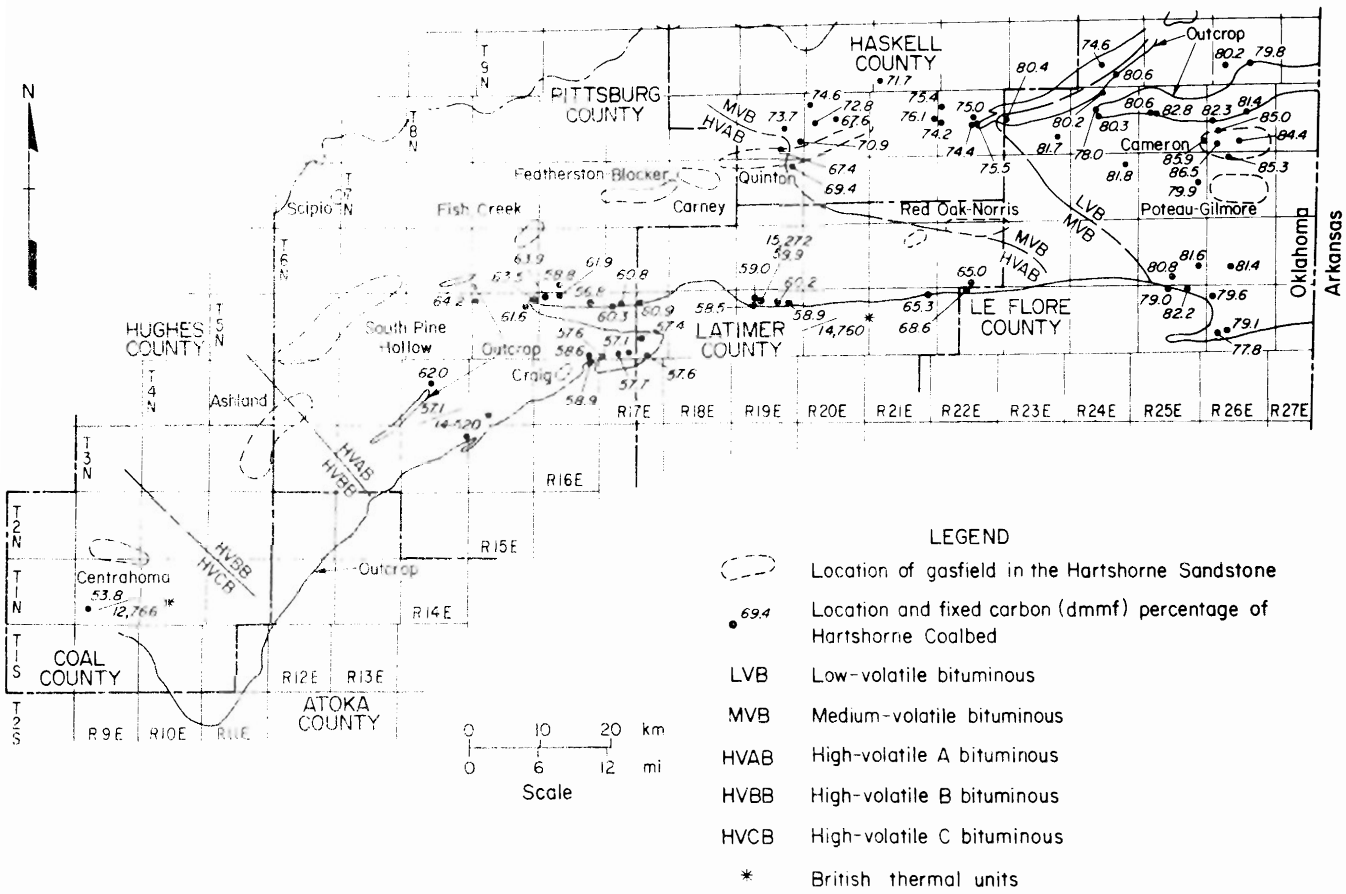

FIGURE 16. - Regional rank map of Hartshorne Coalbeds.

(29, 32). These phenomena have been observed in this study. Five desorption samples (14-15, 17-19; table 2) of various ranks collected from depths ranging from 236 to 278 m (775 to 913 ft) have a methane content from 8.3 to 16.8 cm^3/g (237 to 538 ft^3/T). The two high-volatile A bituminous samples (18-19; table 2) have an average methane content of 8.7 cm^3/T), while the three low-volatile bituminous samples (14-15, 17; table 2) have a much higher average of 14.7 cm^3/g (470 ft^3/T).

An estimate of the change in methane content versus depth must be made on coals of specific rank. Inclusion of all the data in table 2, then, would be inappropriate to estimate methane content for coal of several different ranks. Sixteen desorption samples were from coal of low-volatile rank, one from medium-volatile rank, and two from high-volatile A bituminous rank. Actual data were adequate to estimate methane content of the low-volatile bituminous coals. Because there were only two samples of high-volatile A bituminous coal, a model was used to estimate methane content of the high-volatile A bituminous rank coal in the study area.

Kim (21) developed a general model to estimate the methane content, which includes corrections for moisture, ash, and rank as a function of depth (appendix). The reliability of using this model to estimate the methane content of the Hartshorne Coalbeds was statistically evaluated using the 16 low-volatile bituminous desorption samples. Because the average difference between these desorption samples and Kim's estimates was statistically insignificant (level of significance is 0.61), the model was assumed to be an unbiased estimator of methane content. The model explained slightly more than 60 pct of the total

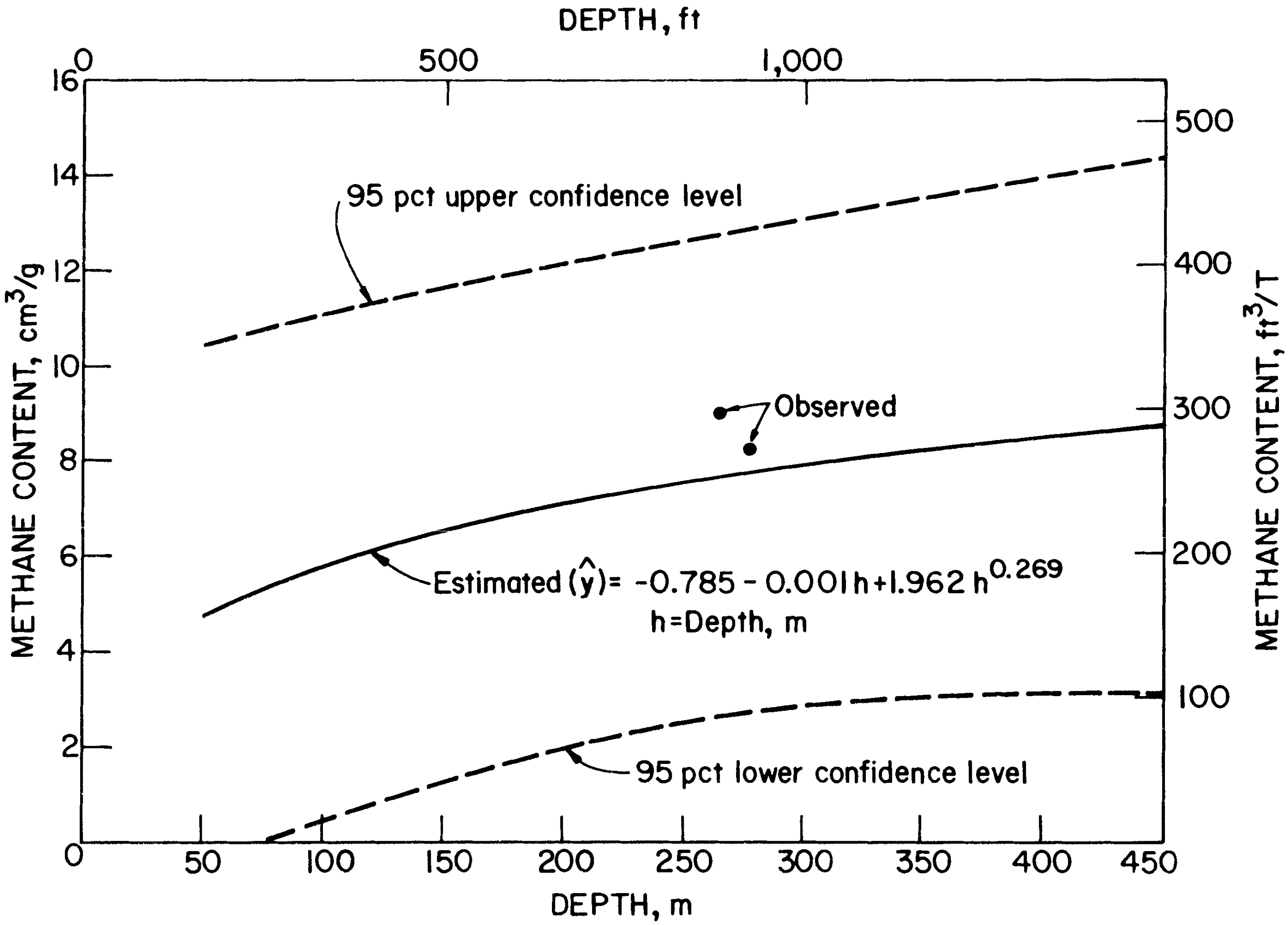

FIGURE 20. - Changes in estimated and observed methane contents versus depth for high-volatile A bituminous Hartshorne coal.

ESTIMATES OF METHANE RESOURCES OF THE HARTSHORNE COALBEDS

The Hartshorne Coalbeds of Pittsburg, Coal, Hughes, and Atoka Counties are estimated to contain 9.2 billion m^3 (325 billion ft^3) of methane. This is a conservative estimate because it includes only coal of minable thickness [>71 cm (>28 in) and <900 m (<3,000 ft) in depth]. Areas of coal with overburdens greater than this are not considered potential mining sites. Table 4 lists the methane potential for Hartshorne Coalbeds at various overburden intervals within the study area. The most notable aspect of table 4 is that 62 pct [5.8 billion m^3 (201 billion ft^3)] of the total resources occur between 600 to 900 m (2,000 to 3,000 ft).

TABLE 4. - Methane resources at various overburdens, Hartshorne Coalbeds

Overburden, m	Methane content,[1] cm^3/g	Estimated resource, billion m^3				Portion of total resource, pct
		Undivided	Upper	Lower	Total	
0 to 305.............	7.1	0	0.4	0.7	1.1	12
305 to 610...........	9.8	.9	.7	.7	2.3	26
610 to 914...........	11.3	2.0	2.1	1.7	5.8	62
Total or average..	9.4	2.9	3.2	3.1	9.2	100

[1] Estimated average, high-volatile bituminous coal.

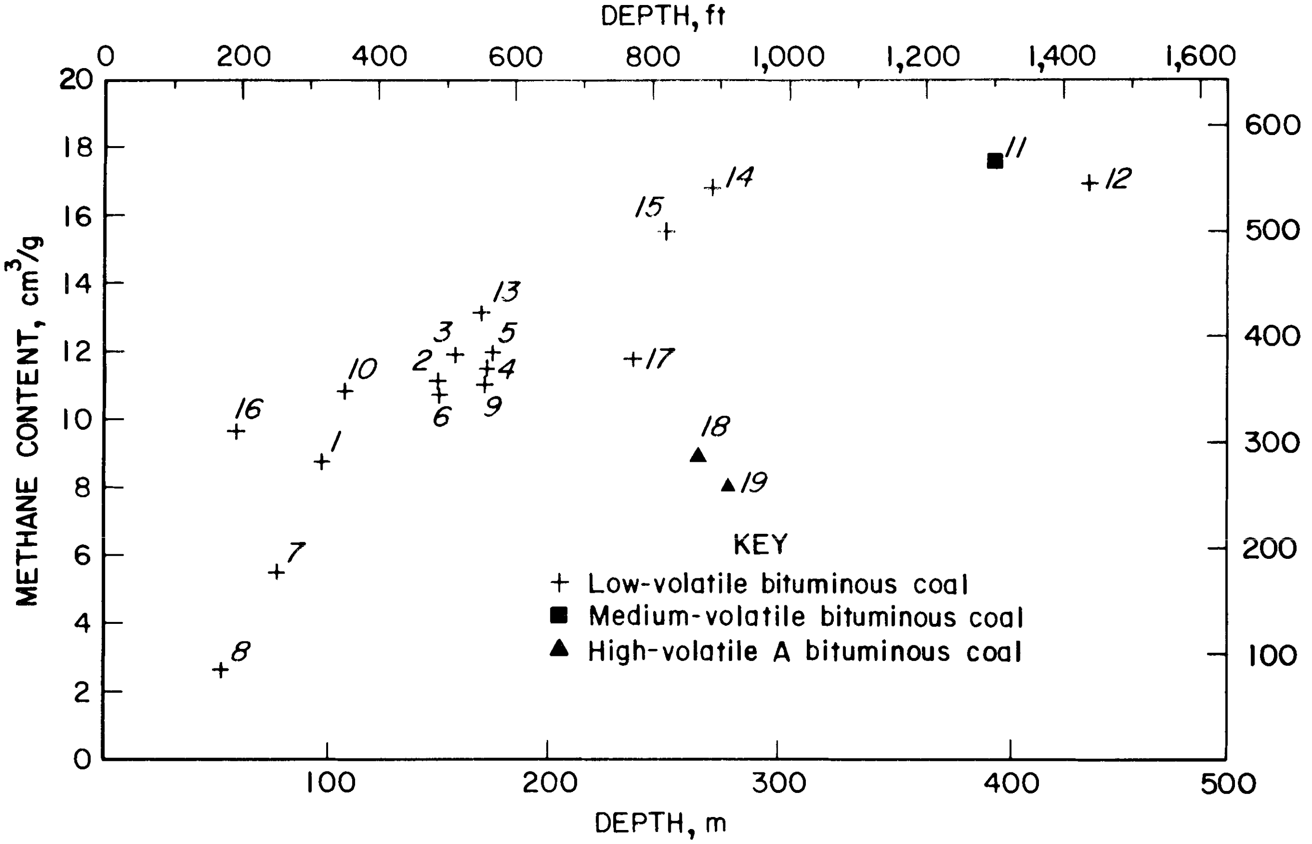

FIGURE 17. - Relationship of Hartshorne coal overburden, rank, and methane content.

variance in the observed methane contents. The remaining unexplained variance was graphically depicted in the confidence interval shown in figure 19. This confidence interval estimates the precision of the model because, over repeated samples, it will include the true methane content 95 pct of the time.

The availability of only two high-volatile A bituminous desorption samples precluded direct comparison of observed and estimated data. This prevented the use of statistical analysis to determine the reliability of Kim's model directly for high-volatile bituminous Hartshorne coal. Figure 20 shows the relationship between the observed and estimated gas contents of high-volatile A bituminous Hartshorne coal. The confidence intervals shown in figure 20 are based on the variance that was found between the estimated and observed low-volatile bituminous coal desorption samples. It should be noted here that Kim recognized that values calculated from the model were consistently high for several observed high-volatile bituminous coals from basins within the United States where the pressure is known to be less than hydrostatic (21). The Arkoma basin is not one of these low hydrostatic pressure basins. Kissell (22) has shown the Hartshorne is comparable to high-pressure coalbeds like the Mary Lee and Pocahontas (table 3). Therefore, Kim's model should not overestimate the methane content for the high-volatile bituminous Hartshorne coals. For these reasons it is felt that Kim's model has allowed for the most accurate estimate available.

TABLE 3. - Gas pressures from various coalbeds in the United States (21)

Coalbed	Location, county and State	Measured pressure, Pa	Depth of base of coal, m
Pittsburgh..............	Marion, WV..........	1,158	283
Do..................	Monongalia, WV......	1,724	244
Do..................	Washington, PA......	1,007	137
Lower Hartshorne........	Le Flore, OK........	1,744	174
Do..................	Haskell, OK.........	4,620	430
Pocahontas No. 3........	Wyoming, WV.........	1,089	233
Do..................	Buchanan, VA........	3,999	431
Mary Lee................	Jefferson, AL.......	2,730	320
Castlegate Subseam No. 3	Carbon, UT..........	1,834	299
Illinois No. 6..........	Jefferson, IL.......	827	224

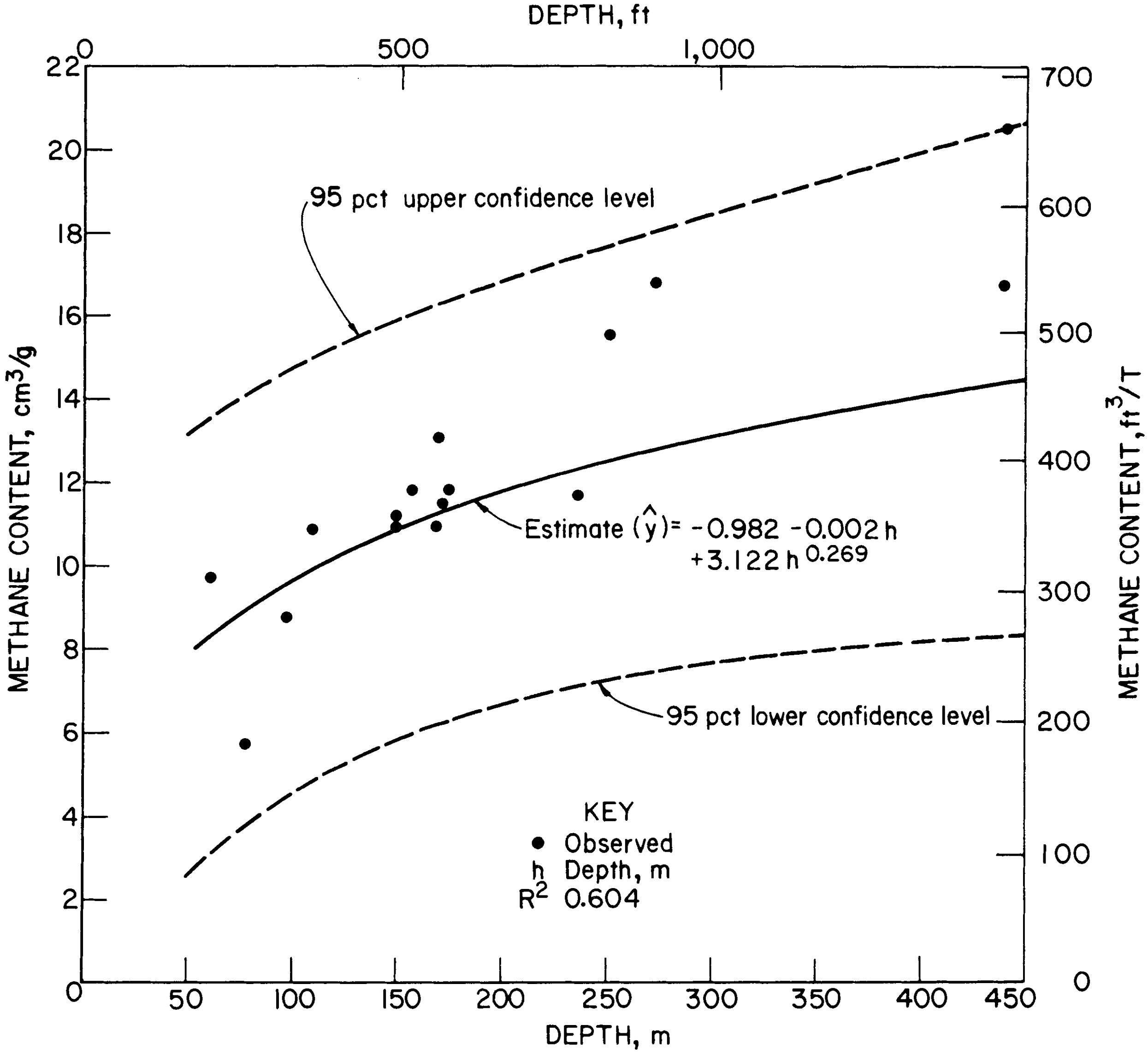

FIGURE 19. - Changes in estimated and observed methane contents versus depth for low-volatile bituminous Hartshorne coal.

The estimated methane resources of 9.2 billion m^3 (325 billion ft^3) represent only one-fourth of the total estimated methane resource for Le Flore and Haskell Counties, OK (18). The considerable difference in resource estimations is probably due to the following:

1. Conservative thickness estimation from density logs in the western portion of the Arkoma Basin compared with more accurate coal-core thickness data in the eastern portion of the Arkoma Basin.

2. At similar depths, high-volatile bituminous coals of the western portion of the basin have approximately 3 to 5 cm^3/g (96 to 160 ft^3/T) less methane than low-volatile bituminous coals of the eastern portion of the basin.

3. The Hartshorne coal in approximately one-half of the study area in the western portion of the basin is at depths greater than 900 m (3,000 ft), and has not been included in this estimate.

OCCURRENCE OF NATURAL GAS IN THE HARTSHORNE FORMATION

Previous sections have provided data establishing the high methane content of the Hartshorne Coalbeds and indicate a potential for hazardous methane emissions in underground workings and a potential for commercial gas production. Complicating the emissions and production problems are the closely associated natural gas fields in the Hartshorne Sandstones (17). In this section, the location of gas fields in the Hartshorne Sandstones will be discussed, the similarities and differences between coalbed gas and natural gas will be characterized, the possibility of communication between these two reservoir rocks will be investigated, and the adverse effects these gas fields will have on underground methane drainage techniques and placement of vertical methane drainage wells will be determined.

LOCATION OF NATURAL GAS FIELDS

The Hartshorne Sandstone of Oklahoma has been producing commercial quantities of natural gas since the early 1900's. The Poteau-Gilmore and Cameron gas fields were among the first gas fields discovered in Oklahoma. In the early 1930's the Quinton gas field became a prolific producer. The Ashland, South Pine Hollow, and Centrahoma gas fields became more prominent in the late 1960's and early 1970's. The locations of these gas fields are shown in figure 21. Most of these gas fields are located along thick trends of Upper and/or Lower Hartshorne Sandstone. Thick Upper Hartshorne Sandstone occurs within the Cameron gas field. Thick Lower Hartshorne Sandstone is associated with the Poteau-Gilmore, Quinton, Carney, Featherston-Blocker, and Centrahoma gas fields. In the Red Oak-Norris, South Pine Hollow, and Ashland gas fields, production has occurred from both Upper and Lower Hartshorne Sandstones. Most of the Hartshorne Sandstone gas fields are combination (stratigraphic and structural) traps. The Ashland and Quinton gas fields are flanked by large-scale faults.

CHARACTERISTICS OF COALBED AND SANDSTONE NATURAL GAS

Identification of distinctive characteristics of coalbed and sandstone natural gas will aid in determining the extent of communication between these respective gas reservoir rocks. Preliminary analysis of some physical and chemical characteristics of gas samples collected from coalbeds and sandstones in the Hartshorne Formation have displayed distinctive trends. It is hoped these trends can aid in identifying similarities and differences between unconventional coalbed gas and conventional sandstone gas. Twenty-six samples (table 5) were collected from eight Hartshorne Sandstone gas fields and eight samples were collected from the Hartshorne Coalbeds (table 6). Analyses consist of stable carbon isotope ratio of methane given in δC^{13} per mil (parts per thousand deviation from the PDB standard) and chemical analysis in percentages. Also the methane proportion of total hydrocarbons (C_1/C_{1-4}) was calculated for all samples analyzed.

TABLE 5. - Hartshorne Sandstone natural gas analysis

Sample	Gas wells	Township and range	Analysis, pct				Carbon isotope of methane, δC^{13} per mil	C_1/C_{1-4}, pct	Estimated rank[2]
			CH_4	CH[1]	CO_2	O_2+N_2+Ar			
C-1	McDow	35 T8N R26E	95.85	0.45	0.80	2.90	-35	0.9953	LVB
C-2	Tucker No. 35	3 T7N R26E	98.22	.67	1.00	.11	-34	.9932	LVB
C-3	Tucker No. 41	4 T7N R26E	89.15	.68	.77	9.40	-35	.9924	LVB
PG-1	Twyman No. 1	28 T7N R26E	89.03	.83	.87	.27	-36	.9916	LVB
PG-2	Hill No. 1	28 T7N R26E	94.51	1.22	.44	3.83	-36	.9873	LVB
PG-3	Jackson	28 T7N R26E	98.17	1.25	.45	.13	-36	.9874	LVB
Q-1	Aldridge No. 4	8 T7N R19E	92.94	5.83	1.00	.23	-43	.9410	HVAB
Q-2	Q. Spelter No. 1	1 T7N R18E	93.42	5.90	.44	.24	-43	.9406	HVAB
Q-3	Q. Spelter No. 4	1 T7N R18E	94.91	4.25	.53	.31	-42	.9571	HVAB
CY-1	Basum No. 2	10 T7N R18E	94.50	3.97	.98	.55	-42	.9597	HVAB
CY-2	Hinton No. 1	9 T7N R18E	90.40	3.91	.31	5.38	-44	.9199	HVAB
CY-3	Vail No. 3	8 T7N R18E	94.90	4.27	.50	.33	-42	.9565	HVAB
FB-1	McFall No. 1	22 T7N R17E	95.20	3.94	.50	.36	-42	.9603	HVAB
FB-2	Pickinal No. 1	19 T7N R17E	95.55	2.38	1.10	.97	-41	.9703	HVAB
SPH-1	McDonald No. 1	35 T7N R12E	88.34	7.93	.43	3.30	-48	.9176	HVAB
SPH-2	O. Morris No. 1	4 T5N R12E	88.55	8.37	.49	2.59	-45	.9136	HVAB
SPH-3	Buse No. 1	28 T5N R13E	87.45	9.83	.48	2.24	-45	.8990	HVAB
SPH-5	Glesse No. 1	33 T6N R13E	86.80	10.27	.34	2.59	-46	.8884	HVAB
SPH-6	Hall No. 1	32 T5N R12E	86.78	5.37	.24	7.61	-48	.9417	HVAB
A-1	Smalley Nos. 1-12	12 T3N R11E	85.40	5.00	.30	9.30	-48	.9447	HVBB
A-2	Lane Nos. 1-28	28 T4N R12E	91.20	5.70	.40	2.70	-48	.9412	HVBB
A-3	Jones Nos. 1-33	33 T4N R12E	89.76	6.34	.37	3.53	-48	.9340	HVBB
A-4	Smith Nos. 1-32	32 T4N R12E	89.95	6.28	.26	3.51	-48	.9347	HVBB
A-5	Cunningham No. 14	14 T3N R11E	88.60	4.63	.14	6.63	-46	.9503	HVBB
A-6	Cunningham No. 24	24 T3N R11E	88.44	4.53	.15	6.78	-47	.9513	HVBB
CH-1	Vaulatta No. 1	31 T2N R10E	88.68	3.76	.19	7.73	-47	.9593	HVCB

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[1] Other hydrocarbons.

[2] Estimated rank of Hartshorne coal associated with individual gas wells: LVB, low-volatile bituminous coal; HVAB, high-volatile A bituminous coal; HVBB, high-volatile B bituminous coal; HVCB, high-volatile C bituminous coal.

TABLE 6. - Hartshorne Coalbeds gas analysis

Sample	Coalbed	Township and range	Analysis, pct				Carbon isotope of methane, δC^{13} per mil	C_1/C_{1-4}, pct	Rank[2]	Fixed carbon,[3] pct
			CH_4	CH[1]	CO_2	O_2+N_2 +Ar				
1	Upper....	26 T8N R23E	58.27	0.04	0.68	41.01	-38	0.9993	LVB	81.7
2	Lower....	26 T8N R23E	83.54	.08	1.08	15.30	-38	.9990	LVB	77.7
3	..do.....	32 T8N R26E	98.50	.07	.08	1.35	ND	.9993	LVB	79.0
4	..do.....	1 T5N R25E	99.25	.02	.10	.63	ND	.9998	LVB	79.0
5	Undivided	1 T8N R21E	97.75	.49	1.60	.15	-44	.9950	MVB	75.0
6	Lower....	8 T8N R27E	89.09	.01	.02	10.88	-46	.9999	LVB	84.0
7	..do.....	21 T5N R16E	88.70	.02	.12	11.16	-56	.9998	HVAB	59.0
8	..do.....	21 T5N R16E	89.08	.04	.10	10.78	-55	.9996	HVAB	59.0

ND Not determined.

[1] Other hydrocarbons.

[2] LVB, low-volatile bituminous coal; MVB, medium-volatile bituminous coal; HVAB, high-volatile A bituminous coal.

[3] Percent moisture and mineral matter free.

Coalbed gas has a very high percentage of methane and very low percentages of all the other hydrocarbons (20). The methane proportion (C_1/C_{1-4}, table 6) of the coalbed gas was found to be consistently in the 99-pct range, independent of rank changes (fig. 22A). The stable carbon isotope ratio of methane was found to range from -38 per mil (δC^{13}) in the eastern portion of the Oklahoma Arkoma Basin to -56 per mil (δC^{13}) in the western portion of the basin (compare table 6 with figure 21). With the exception of sample 6 (table 6), the coalbed gas samples become isotopically lighter to the west. The coalbed methane is isotopically lighter as the coal decreases in rank (less coalification) to the

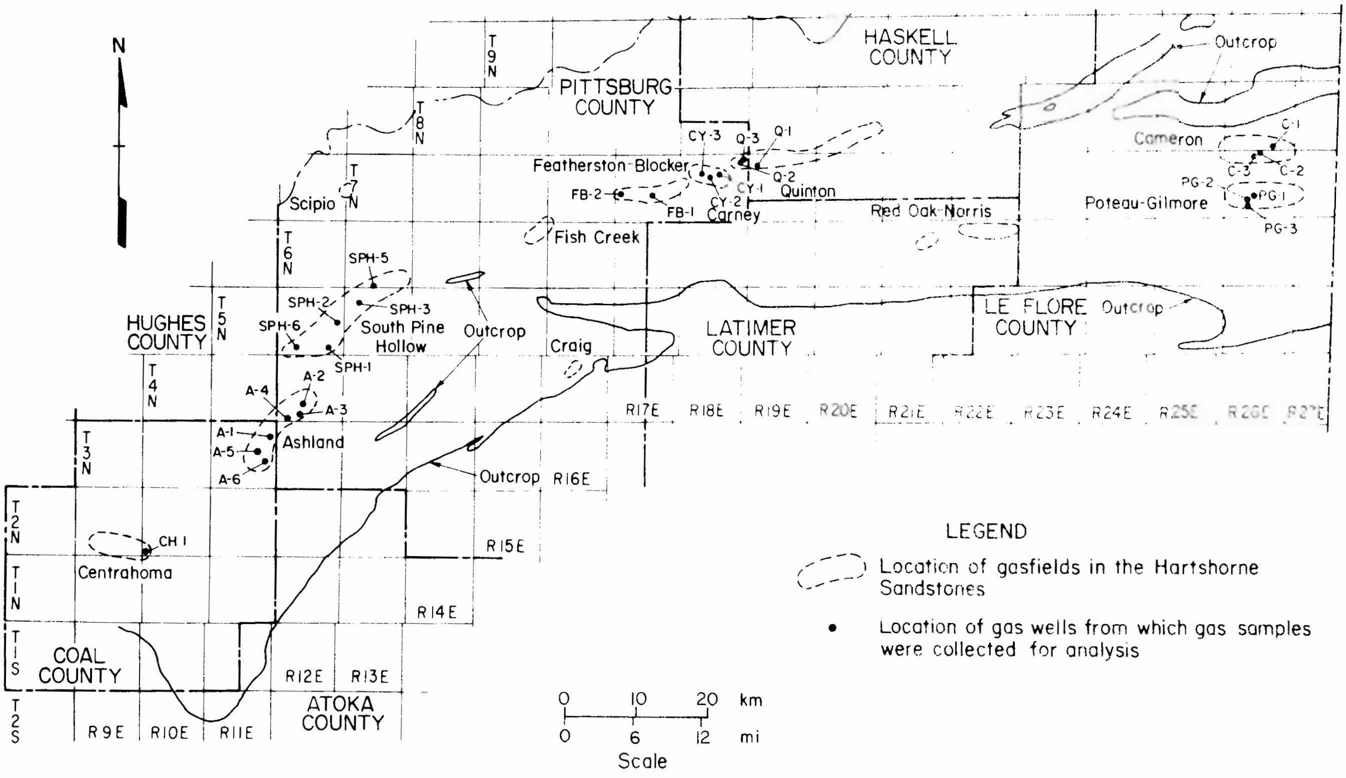

FIGURE 21. - Location of natural gas fields in Hartshorne Sandstones.

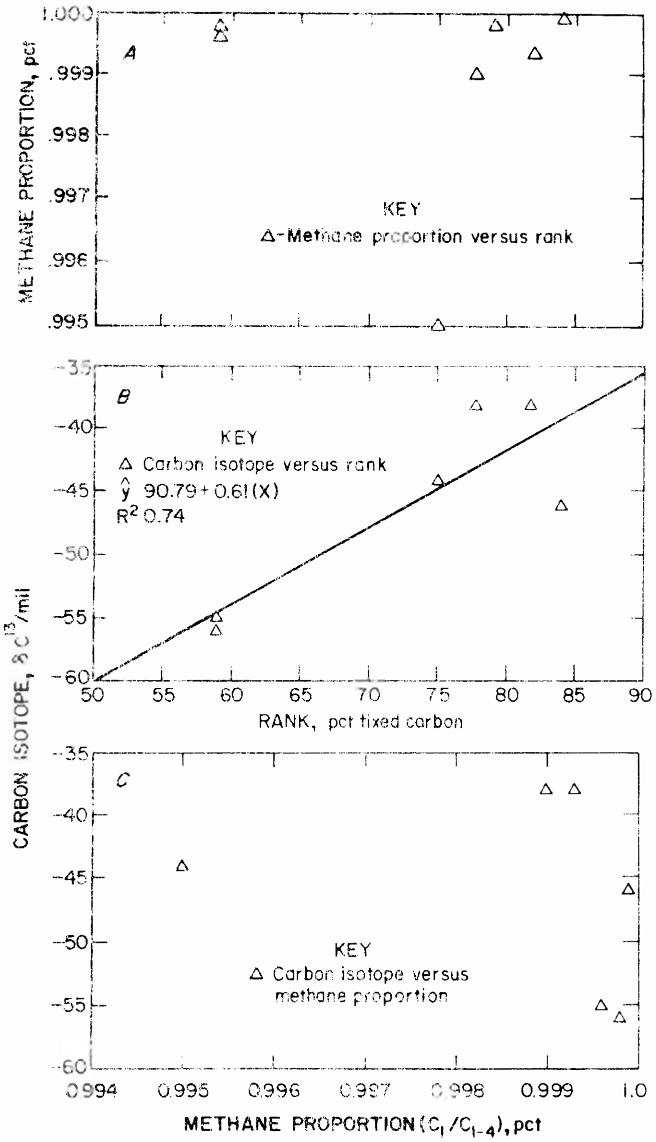

FIGURE 22. - Hartshorne Coalbed gas samples. *A*, Changes in methane proportion versus rank; *B*, changes in carbon isotope ratios of methane versus rank; *C*, changes in carbon isotope ratios of methane versus methane proportion.

west (fig. 16). This relationship implies that the carbon isotope ratio of methane is dependent on rank of associated coal (fig. 22*B*). There does not appear to be any relationship between carbon isotope values and methane proportion of coalbed gas (fig. 22*C*).

Natural gas from the Hartshorne Sandstone displays considerable variation in the carbon isotope ratio of methane and the methane proportion (table 5). Variations in these physical and chemical characteristics of natural gas are probably related to changes in rank of the associated coal (figs. 23*A*-23*B*). As rank of coal increases from west to east across the Oklahoma portion of the Arkoma Basin, the carbon isotope ratio of methane becomes lighter and the methane proportion increases (fig. 23*C*). Analyses of samples from sandstone gas wells indicate that carbon isotope values, methane proportion, and rank are interrelated.

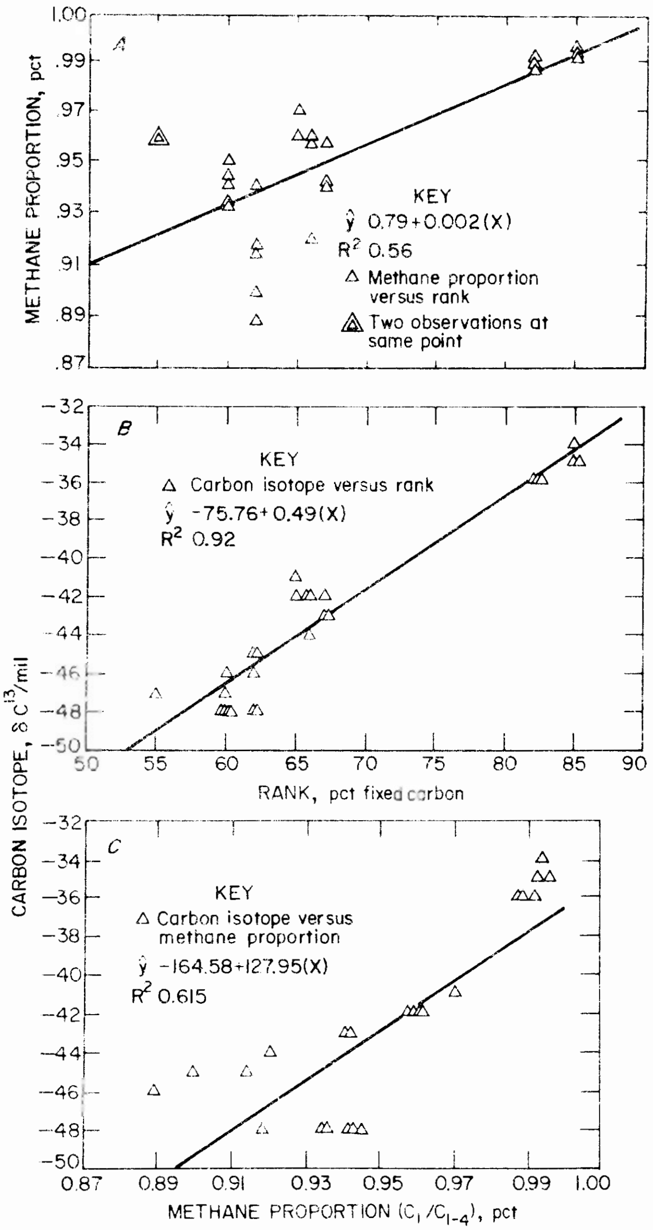

FIGURE 23. - Hartshorne Sandstone gas samples. *A*, Changes in methane proportion versus rank; *B*, changes in carbon isotope ratios of methane versus rank; *C*, changes in carbon isotope ratios of methane versus methane proportion.

Two trends correlated with the west to east increase in rank across the Oklahoma portion of the Arkoma Basin are recognized: Methane gas becomes isotopically heavier in both coal and conventional natural gas and methane proportion of conventional natural gas increases at the expense of heavier hydrocarbons. Previous investigations (3, 27, 31) have shown a relationship between stable carbon isotope ratio of methane and methane proportion with increases in thermal maturation (analogous to increases in rank). These trends only apply for organic matter associated with coal ranking higher than high-volatile bituminous.

The great similarity in physical and chemical analyses of Hartshorne Coalbed and conventional natural gas from eastern portions of the basin leads to at least two possible explanations for the origin of the gas. Large quantities of predominantly methane gas were generated by the coal as coalification occurred (increase in the rank of coal). So much methane was generated in the advance stages of coalification (medium- to low-volatile bituminous coal ranks) that gas migrated from the coalbed into the surrounding sandstones.

Juntgen and Karweil (19) have shown that coal retains only a fraction of the methane generated during coalification. The other explanation would involve physical and chemical fractionation of gas generated from any number of source rocks. These gases, variable in physical and chemical characteristics at lower stages of coalification (high-volatile bituminous coal rank), became both isotopically heavier and increased in methane proportion with increasing coalification (medium- to low-volatile bituminous coal rank). These alternatives explain the similar heavy carbon isotope values and the lack of heavier hydrocarbons in the Poteau-Gilmore and Cameron gas fields of Le Flore County.

The large variations in physical and chemical characteristics of gas recovered from Hartshorne Coalbeds and Sandstone in the western portion of the basin may be the result of differences in the organic source materials. Coalbeds and sandstones of the Hartshorne Formation were deposited primarily in delta plain environments (15) where humic organic matter was predominant over sapropelic organic matter. The hydrocarbons generated from this humic organic matter would be mostly methane (16). However, it has been demonstrated that the Hartshorne delta system prograded toward an open sea to the west and that the Hartshorne Formation contains more marine-influenced facies westward (15). Thus, sapropelic organic matter, which is more common in marine environments, may have been the source of at least part of the hydrocarbons in the western part of the basin. Such sapropelic source materials tend to generate heavier hydrocarbons than humic source materials and this difference may account for variations in carbon isotope values and methane proportions. Additionally, the lower rank of Hartshorne coals in the western portion of the basin indicates that the hydrocarbons are less mature than those in areas of higher coal rank. This could also contribute to variation in carbon isotope values and methane proportions.

USE OF GAS COMPOSITION DATA TO IDENTIFY LEGAL AND TECHNOLOGICAL PROBLEMS IN UNDERGROUND AND SURFACE METHANE DRAINAGE PROJECTS

Identification of gas as either conventional (sandstone) or coalbed in origin could possibly be useful in legal and technical problems. If gas from underground methane drainage projects or vertical methane drainage boreholes producing from coalbeds is proven to be occluded gas, the operator may sell this gas at a deregulated gas price. This is pursuant to Section 107 of the Natural Gas Policy Act of 1978. In December of 1980, the Federal Energy Regulatory Commission and the Oklahoma Corporation Commission recommended for approval the Kerr-McGee Coal Corp. application to sell occluded "coalbed" gas from the Choctaw Mine at a deregulated price (30). This gas was produced from a horizontal borehole methane drainage system operating within the mine. The key to approval recognized by the Commission was that the gas produced from the coalbed did indeed originate in the coalbed.

The composition of gas as indicator of origin is also important to underground methane drainage technology. The great potential for high gas emissions occurring in advancing sections of mines developed in the Hartshorne Coalbeds has already been established. Additional emission problems may occur as these mines approach one of the many Hartshorne Sandstone reservoir rocks. Different methane drainage techniques may be required depending on the immediate source of the gas (coalbed versus sandstone). If high methane emissions from a coalbed are encountered, then conventional horizontal degasification holes, drilled a few hundred meters in advance of working sections at an angle perpendicular to predominant cleat direction in the coal, will produce optimum drainage effects. On the other hand, if methane is emitted from a nearby sandstone reservoir, other methane drainage techniques may be more effective. This gas probably will be emitted into the mine openings through the superjacent and subjacent strata. One way to intercept this migrating gas would be to drill cross measure holes into the floor and roof-rock at angles to the mine opening. This technique is similar to longwall gob drainage with cross measure holes (26).

Once the sandstone reservoir is breached by fracturing of associated strata, the best method may be to drain the reservoir by opening all the gas wells for full production to deplete the reservoir. This raises complex problems of ownership of resources and legal problems that are beyond the scope of this report.

INFLUENCE OF GEOLOGIC STRUCTURES ON DEVELOPMENT OF DEEP MINES AND PLACEMENT OF COALBED METHANE DRAINAGE WELLS

Mine planning and development, the choice of mining system, and the positioning of coalbed methane drainage wells are influenced by the structure of the Arkoma Basin. Throughout the basin, the dip of the Hartshorne Coalbeds is variable, and in places exceeds 20°. Faulting of the Hartshorne Coalbeds has been observed in many old mine workings and is expected to be a serious problem in the southeastern portion of the study area where deformation is the most intense. These structural features must be considered when a mine is planned or methane drainage well is drilled.

The Hartshorne Coalbeds have been evaluated structurally to determine the degree of dip and the intensity of folding and faulting within the study area. Such information will aid in (1) choosing a mining system that will effectively deal with structure-related problems, (2) selecting an in-mine degasification system appropriate for the mining system, (3) estimating the location and degree of faulting, and (4) assessing effects of structure and overburden on the placement of surface methane drainage wells.

In order to evaluate the structure of the Hartshorne Coalbeds in the study area, structural contour and overburden maps were constructed using the gas well and core borehole data [figs. 18 and 24 (envelope)]. Concomitant use of these maps provides insight to the structure-influenced problems anticipated in mining the Hartshorne Coalbeds.

STRUCTURAL SETTING

The Arkoma Basin is a curvilinear trough extending westward from east-central Arkansas to south-central Oklahoma. The basin is bounded by the Ozark Uplift, Oklahoma Platform, the Arbuckle Mountains, the Ouachita Mountains, and the Gulf Coastal Plain (fig. 25).

The basin evolved as a result of tensional and subsequent compressional forces exerted by Ouachita tectonism (2, 6). Broad synclines and intervening,

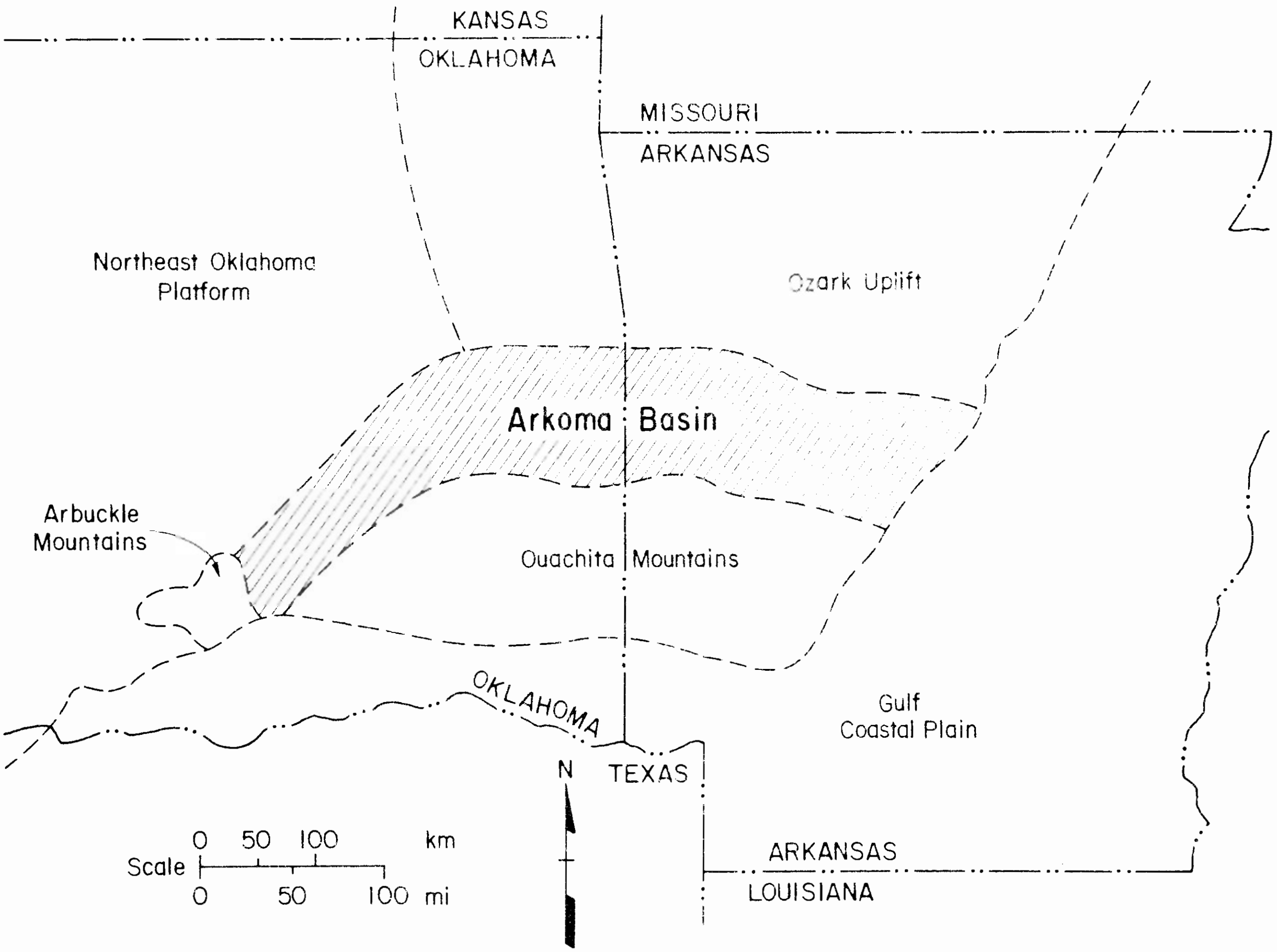

FIGURE 25. - Physiographic province map for western Oklahoma and eastern Arkansas.

relatively narrow anticlines characterize the surficial structure of the Arkoma Basin (33). The axes of these folds lie subparallel to the overall trend of the basin (1). Numerous thrust faults, which also strike subparallel to the basin trend, pierce the crests of the narrow anticlines and underlie much of the surface structure (1-2, 33). The structure beneath the thrust faults horizon is dominated by basement-related normal faults. These faults produced considerable thickness variation in pre-Hartshorne strata (1-2). As the Ouachita structural front is approached from north to south, the amplitude of folds and the displacement along major reverse faults increase (11, 13). In the study area, folding and faulting become more severe from northwest to southeast.

EFFECTS OF FOLDING ON MINE PLANNING AND DEVELOPMENT, MINING SYSTEMS, AND METHANE DRAINAGE PROGRAMS

Folding of the Hartshorne Coalbeds has influenced mine planning and development in the study area. Past mining of the Hartshorne Coalbeds has been confined primarily to areas of very gentle dips adjacent to outcrop (fig. 26). These mines, located near the town of Hartshorne, OK, were developed in strata with an average dip of 15°. Here the mines drove main entries parallel to the coalbed dip with submain entry development parallel to coalbed strike (fig. 26). Rooms were driven updip from submains so the coal could be easily moved from the developing face to railcars along the submains. Because submains were driven

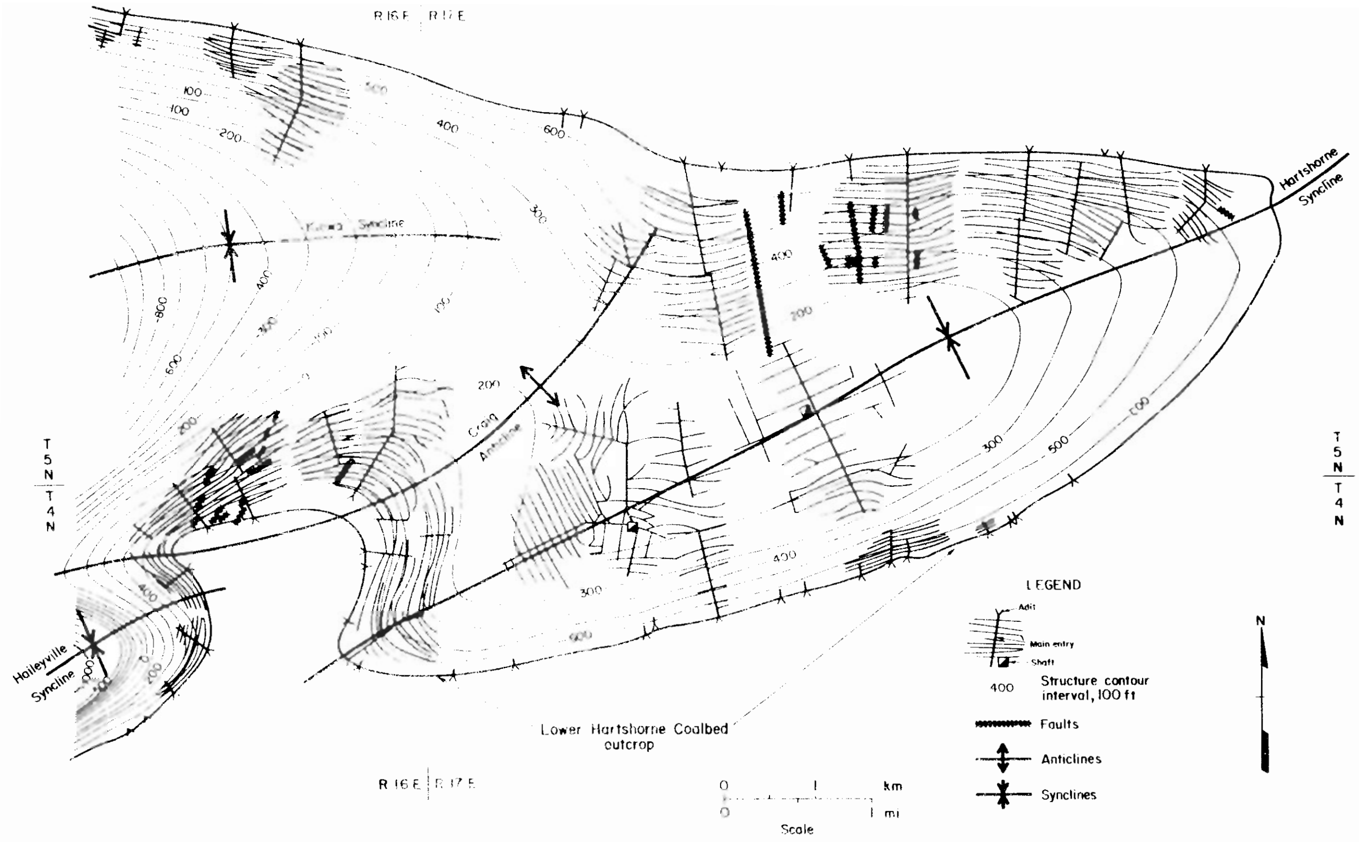

FIGURE 26. - Local structure contour map of Hartshorne Coalbeds showing main and submain entry development of abandoned coal mines near Hartshorne, OK.

along strike (relatively flat), coal could be easily transported to a skip hoist along main entries for transport to the surface.

Present conditions are such that new mines opening in the area must locate in areas of adverse structural setting (compare figs. 3 and 4 with 24). In the study area, folding is most intense in the southeastern portions, close to the Choctaw Fault, but dies out to the northwest (fig. 24). Relatively tight folds such as the Colgate, Savannah, and Craig Anticlines, and the Kiowa and Haileyville Synclines (fig. 24) will prevent development of mines using conventional room-and-pillar techniques. Steeply dipping beds associated with intense folding will generate additional problems that must be accounted for during property evaluation. Along the Hartshorne outcrop in T1S R11E, T1N R12E, T2N R13E, and T3N R14E, dips of as much as 60° are encountered and there is no underground mining. With such high dips, special mining systems must be employed. In the northwestern portion of the study area, folding is less intense and ordinary mining methods may be used.

The placement of coalbed methane drainage wells is also affected by the fold structures of the Arkoma Basin. If the structure of an area is misconstrued or poorly understood, a vertical methane drainage well will be drilled without knowing the depth of the production zone. Folded coalbeds produce problems in an underground methane drainage system because it is often difficult to keep a horizontal borehole within a relatively thin bed when the strike and dip of the bed is continuously changing (fig. 27). Most methane drainage systems have been developed for standard mining with dips of 0° to 20° (23). At dips greater than 20°, different mining systems are employed (i.e., longwall mining, breast and pillar, and undervein development) and these mining systems will require specialized methane drainage techniques.

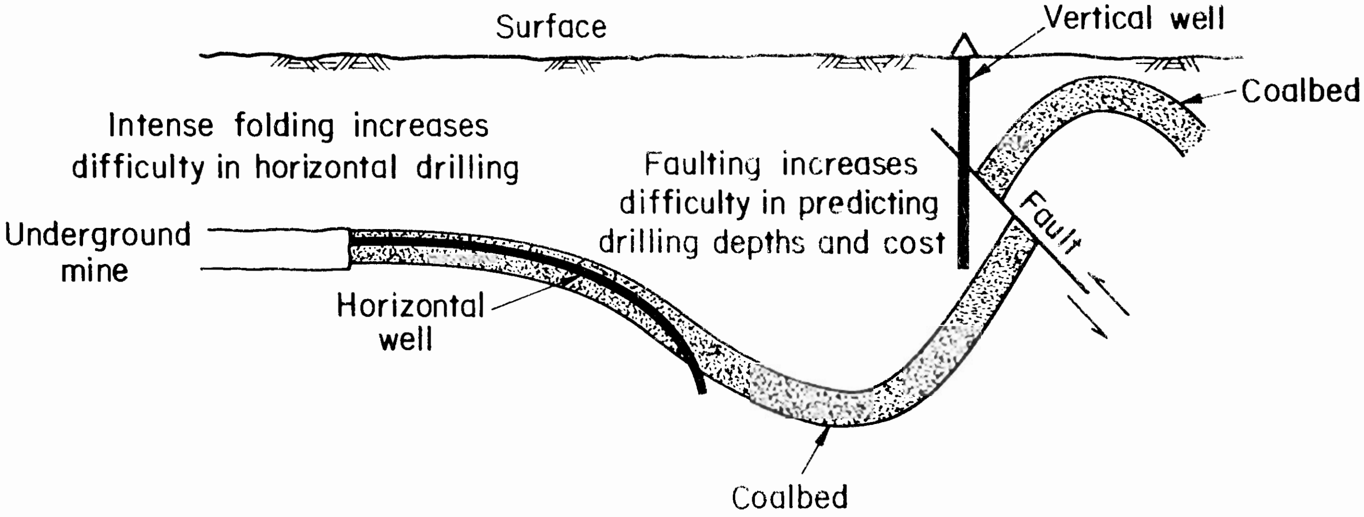

FIGURE 27. - Effects of variability in folding and faulting on drilling methane drainage systems.

EFFECTS OF FAULTING ON MINE PLANNING AND DEVELOPMENT, MINING SYSTEMS, AND METHANE DRAINAGE PROGRAMS

Numerous faults throughout the study area present many obstacles to mine planning and development. Large-scale faults, such as the Choctaw Fault, Phillips Fault, Ashland Fault, and Penitentiary Fault, with hundreds of meters of offset (fig. 24), are natural barriers to mine development. These faults generally trend from northeast to southwest and extend 5 to 16 km (2 to 10 mi) along strike. They formed as a result of compressional forces arising during Ouachita tectonism (6). These large-scale faults are concentrated in the southeastern portion of the study area, nearest the Ouachita structural front.

In addition, a multitude of small-scale faults are found throughout the study area. These faults are not mapped on the structure contour map because of their small scale, but are found on numerous mine maps of the area. Although displacement on these small-scale faults is not great enough to inhibit mining, they have created serious mine development and roof control problems (fig. 26). These minor faults are generally oriented subperpendicular or subparallel to local structures, and are generally several hundred meters to 1 km (0.6 mi) in length.

Faults may also introduce problems into a methane drainage program that uses both vertical and horizontal boreholes (fig. 27). Faults are difficult to drill through and make projections of the coalbed depth difficult to ascertain. Additionally, the vertical displacement of faults can compartmentalize the coalbed gas reservoir and prevent effective drainage of methane. Brecciation and fracturing associated with faulting generally increase the permeability of coal and produce increased gas flows in the vicinity of a fault, but can present problems in maintaining an open hole. Faults that extend to the surface may either emit methane into the atmosphere or infuse water into the coal thus limiting water removal effectiveness.

SUMMARY AND CONCLUSIONS

The Hartshorne coal and associated gas remain largely unproduced because of several complex and somewhat interrelated geological factors. Approximately 1 billion t (1.1 billion T) of coal in place remain untouched by standard mining systems. Methane resources, estimated at 9.2 billion m^3 (325 billion ft^3) have only recently been tested for production potential. Basic engineering and geological research indicated several potential problem areas related to mining and gas resource potential: Variations in thickness of coals, increases in methane content with increases in overburden and rank, engineering and legal gas production problems because of close association of Hartshorne Coalbeds and Sandstones, and variability in folding and faulting of the Hartshorne Formation.

Detailed geological maps presented in this report will help to plan for or avoid many geologically influenced mining and methane drainage problems. Areas of minable coalbeds have been delineated thereby providing a basic reference for exploration programs. Investigations of methane content have indicated a need for a comprehensive methane control program in underground mines. This large methane resource could also be of economic significance in the future.

Variations in methane content must be understood for designing methane drainage programs and mine ventilation. Locations of gas-producing Hartshorne Sandstone are provided to indicate the additional health, safety, and production problems that will occur in certain portions of the basin. Also, data provided on the physical and chemical characteristics of coal and conventional natural gas allows recognition of the source of gas emissions and/or flows. Examination of structure-related problems and the locations of areas expected to have these problems are given.

The data provided in this report should be used by engineers and geologists in planning for the safest, most productive mining and methane drainage systems available for the Hartshorne Coalbeds of the Western Arkoma Basin.

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APPENDIX.--APPLICATION OF KIM'S MODEL TO THE HARTSHORNE COALBEDS

Kim's general equation (21)[1] for estimating the methane content (cubic centimeters per gram) of coal in place is

$$V = \frac{(100 - \text{pct moisture} - \text{pct ash})}{100} \times \frac{V_w}{V_d}\left[K_o(0.96 \times h)^{N_o} - b\ (1.8 \times h/100 + 11)\right], \qquad \text{(A-1)}$$

where h = depth in meters.

Values for V_w/V_d, K_o, N_o, and b are dependent on the rank of the coal. Representative average values for these variables were determined for the low-volatile and high-volatile A bituminous Hartshorne coals. The following data are considered to be the best available values for estimates of methane contents at different ranks:

	Low-volatile	High-volatile A
Moisture..........................pct..	10	10
Ash...............................pct..	5	5
Fixed carbon (FC).........pct (dmmf)[1]..	82	67
Volatile matter (Vm).......pct (dmmf)..	18	33
Temperature constant (b)........cm^3/g..	0.14	0.14
Ratio of adsorbed gas in wet and dry coal V_w/V_d..........................	0.75	0.60
Rank constant (k_o = 0.8 FC/Vm + 5.6)...	9.24	7.22
Rank constant (N_o = 0.315 - 0.01 FC/Vm)	0.2694	0.2947

[1] Dry mineral matter free.

The above values can be inserted into equation A-1 to produce the following simplified equations:

$$ELV = -0.982 - 0.002 \times h + 3.122 \times h^{0.269}, \qquad \text{(A-2)}$$

$$EHV = -0.785 - 0.001 \times h + 1.962 \times h^{0.269}, \qquad \text{(A-3)}$$

where ELV = estimated methane content of low-volatile bituminous Hartshorne Coal, cubic centimeters per gram,

EHV = estimated methane content of high-volatile bituminous Hartshorne coal, cubic centimeters per gram,

and h = depth, meters.

Equation A-2 was used to generate figure 19, and equation A-3 generated figure 20.

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[1] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.